A fluvial geomorphic investigation into channel capacity changes at the Barmah Choke using multiple lines of evidence

For

The Murray–Darling Basin Authority

By

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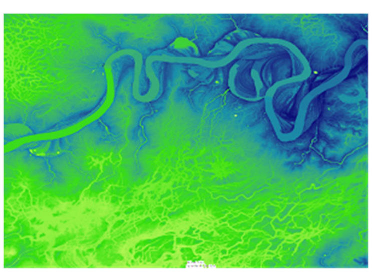
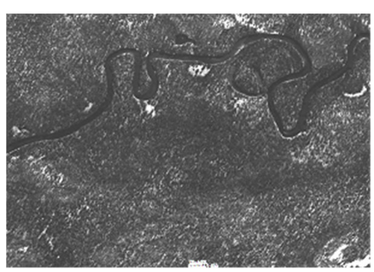
Executive summary edited by Tim Cummins


Acknowledgements

Ian Rutherfurd is thanked for his constructive and diligent reviews of several versions of this report. They have improved the document significantly. Tim Cummins did a sterling job translating the executive summary into something more accessible.

The Rivers of Gold (ARC grant number DP160100799) team including Prof. Susan Lawrence, Dr. Peter Davies, Ms. Jodi Turnbull, Prof. Ian Rutherfurd and Assoc. Prof. Ewen Silvester have been instrumental in revealing the impacts of historic gold mining in Victoria.

Citation: Grove, J.R., 2021. *A fluvial geomorphic investigation into channel capacity change at the Barmah Choke using multiple lines of evidence*. Report for the Murray–Darling Basin Authority, Canberra, ACT

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Executive summary

E 1. Executive Summary: Problem statement

About 25,000 years ago, an uplift along a north-south geological fault line near Deniliquin and Echuca led to the creation of the Barmah-Millewa Forest. The reach of the River Murray running through the forest is so narrow and shallow that under natural conditions flows would often spill onto the floodplain to generate and sustain the forest. This reach of the Murray system is generally referred to as the Barmah Choke. It naturally controls the flow rate that river operators can deliver downstream through the regulated river.

The capacity to pass flows through this part of the river is reducing. Gauge data from Picnic Point show that the flow rate that can be released from Yarrawonga Weir without causing overbank flows is lower now than it was 30 years ago. A recent survey of river bathymetry, over 78 km, has also shown that, compared to the expected undisturbed loads of bed sediments, an excess of bed sediment has accumulated in the river channel upstream of Picnic Point sometime after European settlement.

This study investigates the physical forms and processes that influence the capacity to deliver water through the Barmah-Millewa system. New data will be analysed on the volumes and distribution of coarse sands in the riverbed between Yarrawonga Weir and Picnic Point. Available evidence on the how river system operated before and after disturbance will be presented. Different drivers and rates of change, from both natural and human actions, will be used to help quantify volumes of coarse sediment that have been mobilized into the riverbed. Finally, the future changes for the river channel will be predicted.

E 2. Evidence for a change in channel capacity at Picnic Point

The lowest channel capacity of the River Murray between Lake Hume and South Australia is at the Barmah Choke (Ladson and Chong 2005) (**Figure E0-1**).

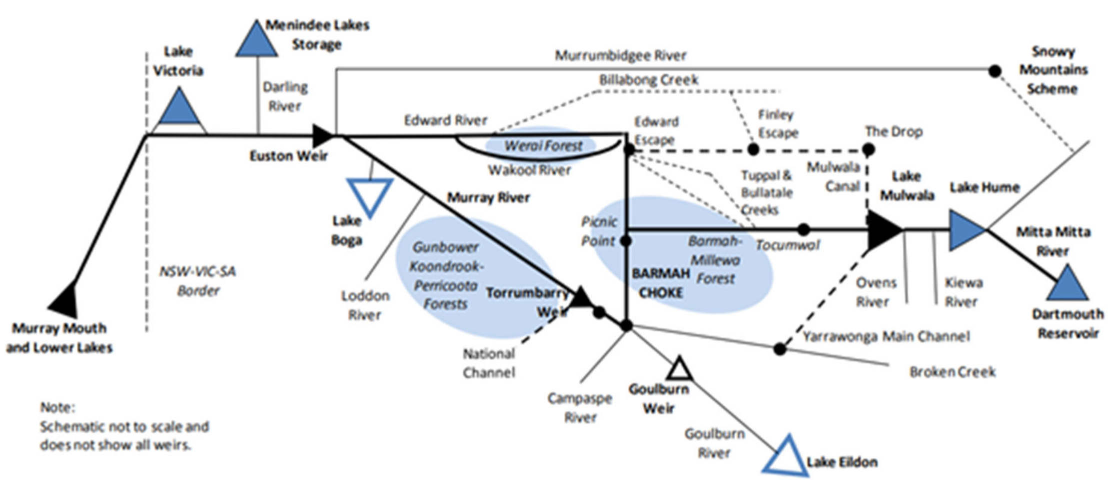

Figure E0-1. A schematic representation of the River Murray system showing the Barmah Choke in the centre (SKM 2012).

Releases from Yarrawonga Weir must currently be kept below 9,200 ML/d to keep the water in the channel at Picnic Point; this is down 19 %, from the 11,300 ML/d that could be kept in the channel in the early 1980s. The currently available detailed evidence from 2001-2017 suggests limited changes to the position of the main channel, the width of the main channel, the number of effluent channels, or the sinuosity of channels in the Barmah-Millewa Forest over this period. This indicates that the channel itself appears to be remaining relatively constant in form whilst the capacity is changing.

Given that relatively constant channel form, there are two possible explanations for reduced channel capacity at Picnic Point. One possibility, as suggested by MDBA (2009), is that the channel's artificially modified levees are now less effective – this would result in water spilling out of breaches in the levees at lower flows. Under this possibility, the channel's cross-sectional area may not have changed substantially. The other possibility is that sediment may have built-up in the channel, which is reducing its cross-sectional area, and therefore it is also reducing the capacity to deliver water through the channel.

E 3. Evidence of large volumes of coarse sand build-up in the river channel

In 2018 the MDBA organised for a 78 km bathymetric survey of the River Murray from Bullatale Creek to Barmah Lake (River Murray chainages 1770 to 1858 km). The water depths measured in the survey showed dune forms on the riverbed indicative of mobile sand. They also revealed that pools at meander bends had filled with sediment (**Figure E0-2**) (Water Technology 2019). The observed volume and extent of bed sediment was unexpected, therefore it triggered further investigation.

In March 2020, a sub-bottom profiler (SBP) survey measured the depths of mobile riverbed sediments along 24 km of the River Murray (**Figure E0-3**) from chainages 1787 to 1825 km (SA Water 2020). Over 4 m of sediment was measured in some meander pools, confirming the observations in the bathymetric survey, and indicating the average thickness of bed sediment was 1.09 m. For every kilometre of river length in this reach, 84,000 m^3 (112,000 tonnes) of sediment was estimated to be on the bed.

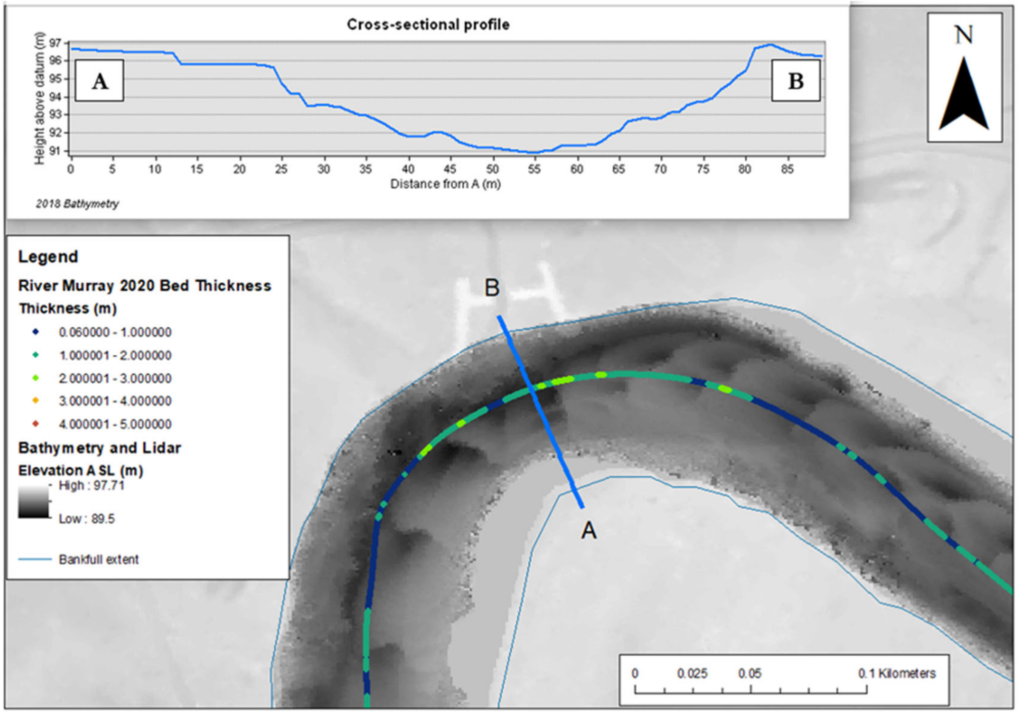

Figure E0-2. *Cross-section of meander bend showing depths based on 2018 bathymetry. Deep pools are to be expected on the outside of river bends, but, near to B, what was a pool is now covered by mobile dunes of sediment. Flow is from right to left of the image and the cross-section starts at A and finishes at B. In-channel the lighter colours indicate the crests of the dunes and the darker colours their troughs.*

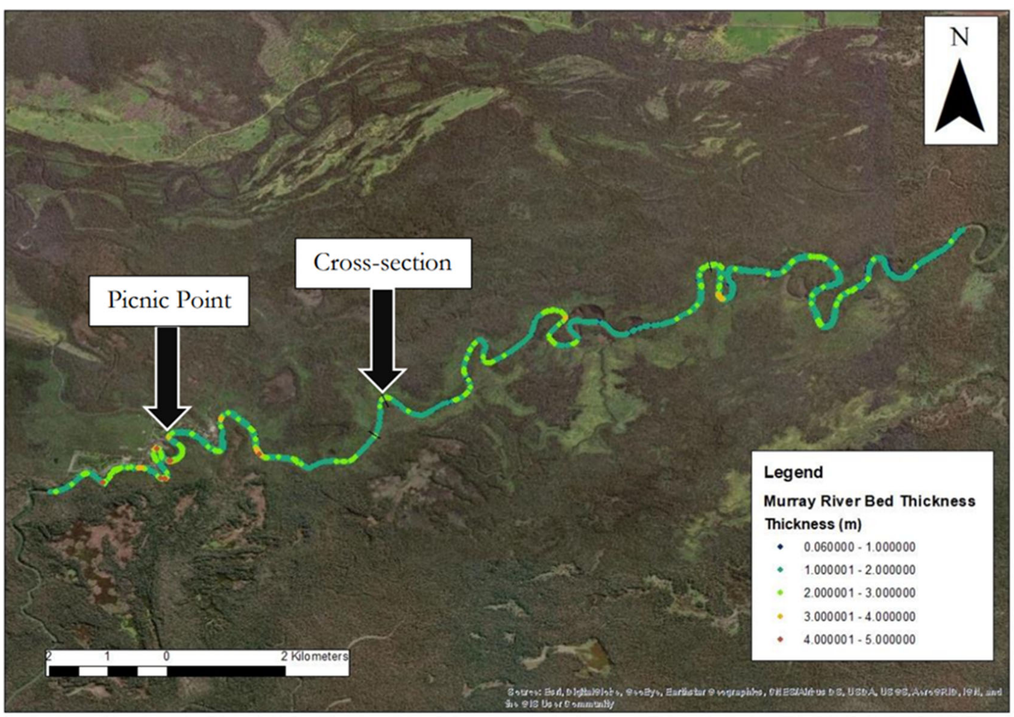

Figure E0-3. *The extent of the 24 km pilot sub-bottom profiler survey undertaken in 2020, the bed sediment thicknesses are shown by classifying them into 1 m intervals. Picnic Point is near the western end of the surveyed reach and the cross-section in **Figure E0-2** is labelled (SA Water 2020). Flow is from right to left in the image.*

The 2020 SBP survey (SA 2020) did not indicate a discrete pulse of bed sediment as there was no significant decline in sediment thickness upstream. Further SBP surveys were undertaken in 2021 (SA 2021a; 2021b) to extend the original data and quantify sediment depths from Yarrawonga Weir to Barmah township (**Figure E0-4**). The combination of the 2020 and 2021 data revealed mobile bed sediment that has built up on the bed and infilled pools with a thickness of 1.21 m from Yarrawonga Weir to Barmah township.

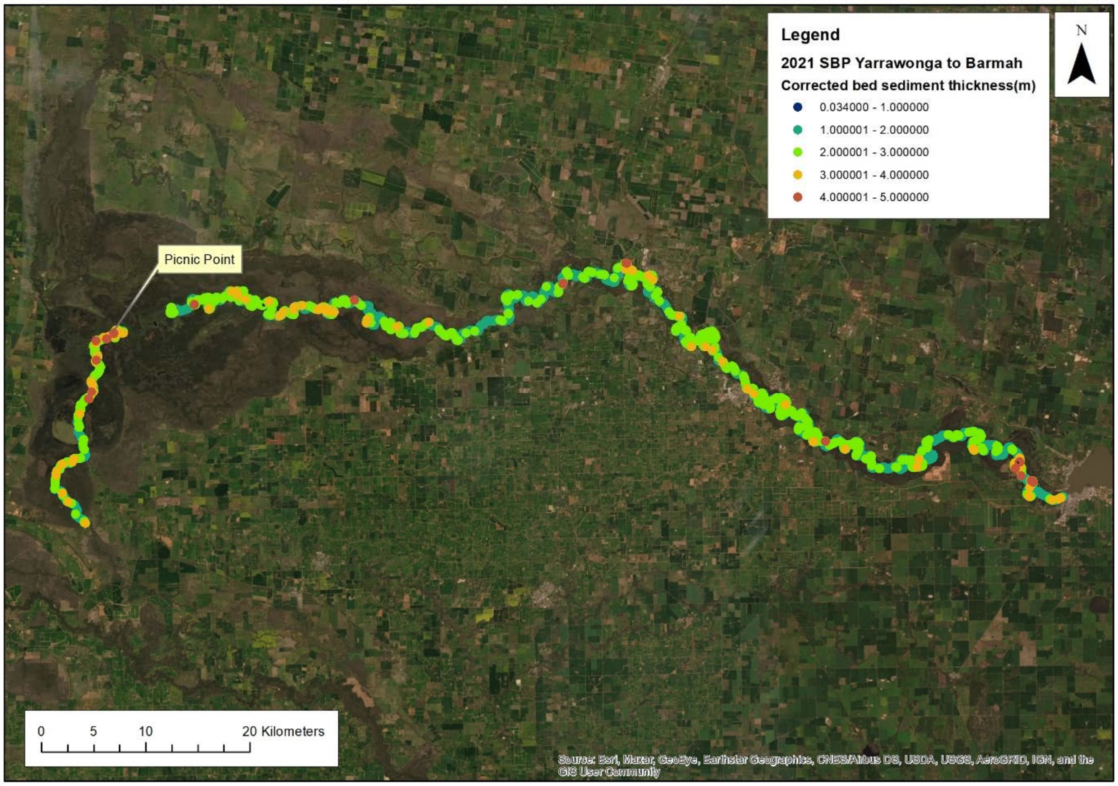

Figure E0-4. *A map of the length of the River Murray where 2021 sub-bottom profiler surveys were undertaken between Yarrawonga Weir and Barmah township, with bed thicknesses classified in 1 m intervals (SA Water 2021a; 2021b). These surveys extended the 2020 survey (**Figure E0-3**).*

Samples of the riverbed sediment were taken from Bullatale Creek to Barmah township and their grainsize distributions analysed **Figure E0-5** (Water Technology 2020; 2021). The sampling revealed that most samples were comprised of greater than 90 % coarse sand. There was also no clear downstream fining of the sediment size, however, upstream of Picnic Point there was less variability.

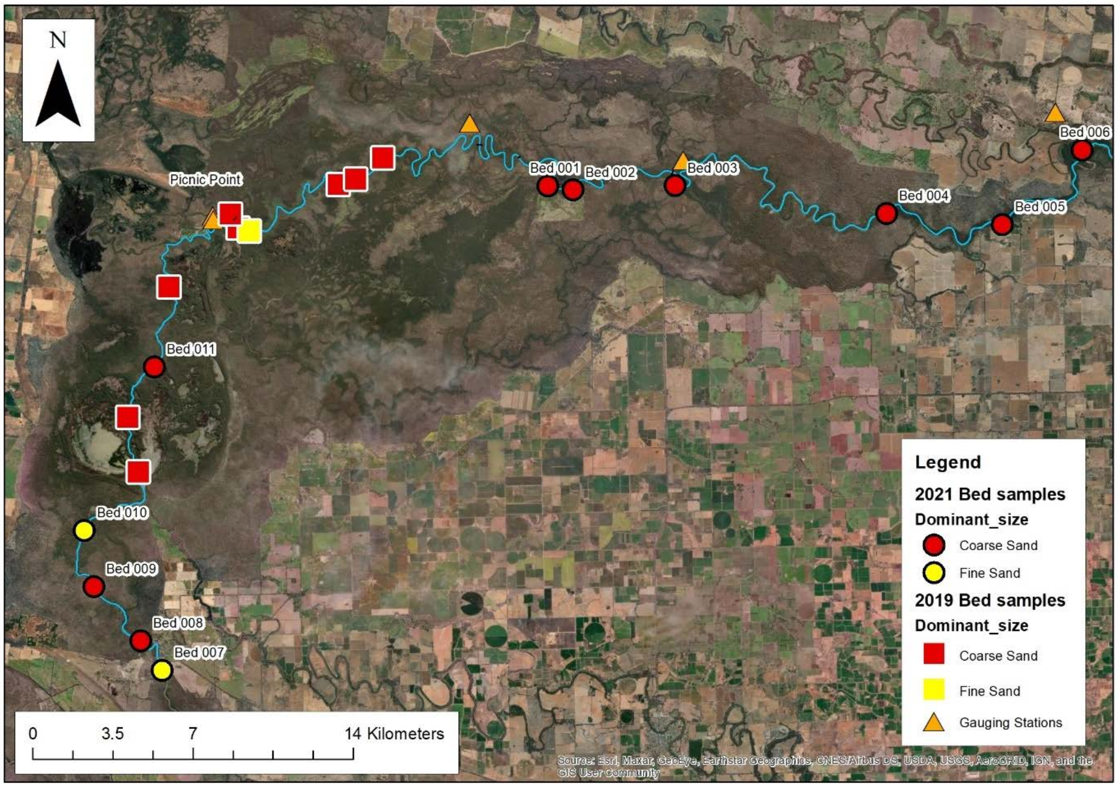

Figure E0-5. Riverbed sediment sampling locations on the River Murray through the Barmah Forest (Water Technology 2020; 2021).

Two study reaches were defined from the SBP data to aid in the understanding bed sediment supply and transport that may have constrained channel capacities.

- Reach 1: Yarrawonga Weir to just upstream of Bullatale Creek (119 km).
- Reach 2: Bullatale Creek to Picnic Point (68 km).

The volume of bed sediment in Reach 1 was estimated as 16 million m^3 and assumed to comprised of the same coarse sand sampled downstream. The volume of bed sediment in Reach 2 was calculated to be 7 million m^3. Overall, there was 23 million m^3 of coarse sand with an average depth of 1.22 m estimated to be in the channel of the River Murray between Yarrawonga Weir and Picnic Point. This will be reported as >20 million m^3 to account for any quantification errors.

E 4. The river channel in context

Upstream of the Barmah-Millewa Forest the River Murray channel is a trench inset in a narrow floodplain around 3 km wide. The river has bankfull widths of 90–120 m and depths 5.5–10 m (Rutherfurd and Kenyon 2005). The most prominent features of the reach are the sandy beaches on point bars.

The triangular shaped Barmah-Millewa Forest is an alluvial fan (**Figure E0-6**). Its apex is downstream of Bullatale Creek and the fan edges extend to the Cadell Fault. Once the river enters this fan it decreases in sinuosity, sandy point bars disappear, silty-clay levees appear, and the bankfull width decreases (Rutherfurd and Kenyon 2005). The technical name for this type of river is a Distributive Fluvial System (DFS) (Gower *et al.* 2020). Unlike most river types, in distributive systems the main channel loses water flow as it continues downstream. This is a result of flows out of the main channel into effluent streams (in the absence of any major tributaries). The beds of the effluent streams are often higher than the bed of the main channel. Therefore, while the effluents take some of the fine suspended sediment loads from the main channel, they leave most of the coarser sediment in the main channel bed. Consequently, the main channel narrows in width, and decreases in depth as it continues downstream, and it gradually fills with bed sediment over time until it can no longer carry all the delivered water flows. Once this happens, a large flood can lead to an 'avulsion', that is, the rapid formation of a new main channel across the alluvial fan, which is capable of carrying the delivered flows.

The Barmah-Millewa Forest covers a network of effluent channels that take high flows from the Murray and distribute them over the forest. Since 1959, or thereabouts, river operators, forest managers, and, more recently, environmental water managers have constructed regulators on these effluents to control flows from the River Murray to the forest. The decrease in channel widths moving downstream in the Choke, and the reduced dispersal of high flows into the Barmah-Millewa Forest, also lower the river's ability to transport coarse sediments through the channel.

Downstream of Picnic Point the channel crosses over ancient lake beds and receives flows from the re-joining of upstream effluents. The result is a low sinuosity channel that is wider and shallower than upstream.

Under natural conditions this river system would be expected to have had relatively low sediment loads, and those loads would have been mainly derived from upstream of Yarrawonga, as there are no tributary inputs. The transportation of those loads would have varied significantly with the hydrology. Floods would have transported significantly higher loads than other flows, while during droughts sediment transport would have been very low or non-existent.

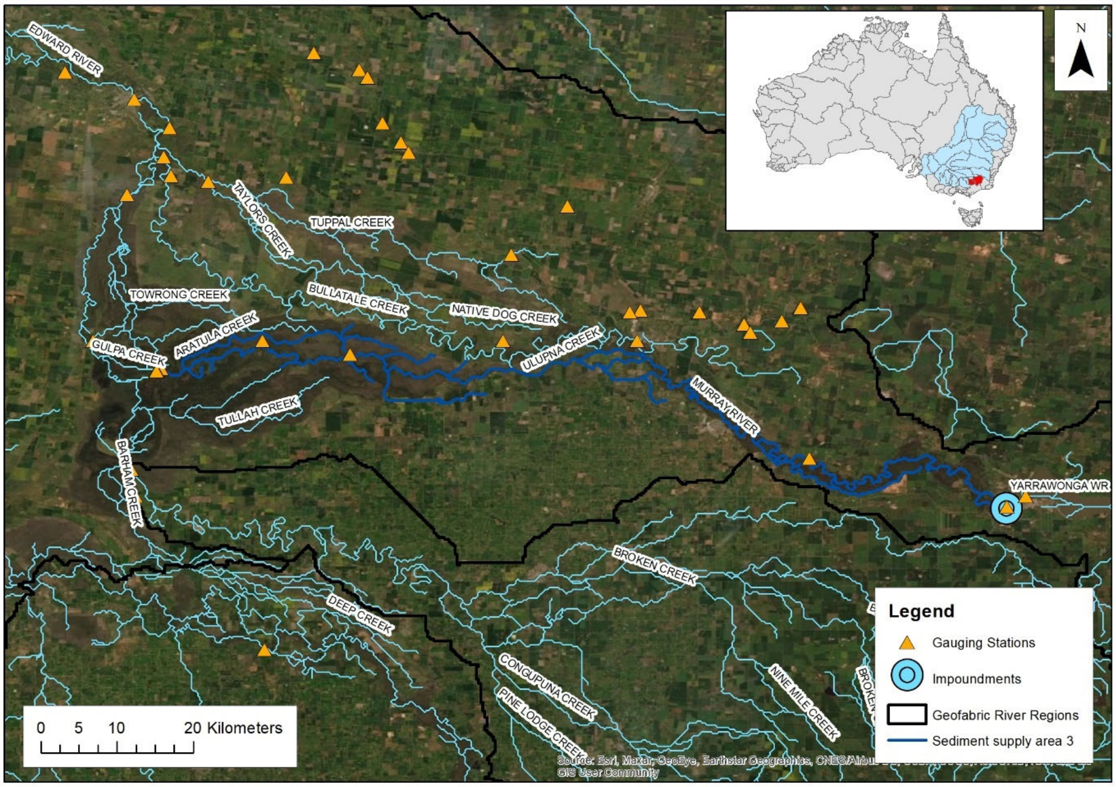

Figure E0-6. *A map of the River Murray between Picnic Point and Yarrawonga Weir showing major waterways in the Bureau of Meteorology (BOM) Geofabric.*

E 5. Historic changes to the River Murray

Rutherfurd *et al.* (2020) summarised the human-induced changes in the River Murray into four main periods based on changes to the finer sediments carried in suspension (**Table E0-1**) (**Figure E0-7**).

1. Aboriginal period (before 1840)
2. The gold and gully period (1850s–1930s)
3. Hiatus period (1930s–1960s)
4. Regulation period (1960s–Present).

These four periods caused several different changes to the sediment and flow in the River Murray, and their impacts on the Barmah-Millewa Forest occurred at different scales. Some are at the local scale, such as the building of Lake Mulwala, some are at the catchment scale such as land clearance; others are at multiple scales, such as desnagging. The combination of human-induced changes to sediment supplies and river flow patterns, especially in the last 150 years, means that sediment transportation at the Choke would also be expected to change. This is true for coarser bed sediments as well as the finer suspended sediments.

Table E0-1. *Human impacts in the River Murray adapted from Rutherfurd et al. (2020)*

Period	Human impact	Likely impacts from Yarrawonga Weir to Picnic Point
Aboriginal	• Fire: Changed land cover over millennia.	• Potential for minor alterations in catchment runoff and hydrology.
Post-1840s	• Fire regimes changed in frequency, intensity, and season. • Increase in erosion rate throughout the Murray-Darling Basin.	• Potential for slightly higher sediment yields.
1840s-1920s	• Clearing, drainage and gullying: European squatters, introduction of sheep and cattle. Coincident with gold mining, population expansion, agriculture, forest clearing, swamp, and floodplain drainage. • Increase in erosion and sediment mobilization throughout the Murray-Darling Basin.	• Decreased surface roughness, reduced evapotranspiration, resulting in higher hillslope runoff causing gullying and sheet erosion. • Increased sediment mobilization into the channel alongside increased discharge.
1851-1930	• Gold mining: quickly spreads throughout the basin by 1860. • Huge increase in sediment supply mainly from the southern basin—Upper Murray, Kiewa, Ovens, Loddon, Campaspe Rivers.	• Change in the timing and volume of flows due to mining operations. • Increase in the sediment supply from tributaries.
1864-1869	• Desnagging: River Murray between Albury and Echuca >3,000 large snags were removed. Wood removal would have increased in-channel sediment movement throughout the river length.	• Increased flux of bed sediment. • Increased instream velocities. • Channel enlargement – width and depth.
1870-1898	• Flow confinement: Effluent channels blocked; flood levees constructed especially after 1870 Great Flood. By 1898 Echuca to Swan Hill works blocked floodwaters on Victoria side to maintain freshwater lakes. • Flow concentrated in channel, increase sediment transport, reduces water losses to floodplain.	• Increase in channel velocities resulting in a greater flux of bed sediment. • Reduced sediment deposition onto the floodplain.
1880	• Desnagging: River Murray was cleared of the largest logs (Trueman 2011). Wood removal would have increased in-channel sediment movement. Throughout the river length. Along most of River Murray and lowland tributary sections.	• Increased flux of bed sediment. • Increased instream velocities. • Channel enlargement – width and depth.
1919-1939	• Weirs: 13 low-level, run-of-river weirs. Initially for river navigation, now maintain hydraulic head for irrigation channels. Between Albury and Darling River junction: Torrumbarry Weir (1919), Euston Weir and Lock 11, Yarrawonga Weir (1939), and Lock 10 downstream of the Darling Junction. • Trap sediment by converting hundreds of kilometres of riverine environment into a lake.	• Trapping of sediment in weir pools. • Clearwater scour downstream.
1917-Present	• Major dams and flood mitigation: Hume Weir (1936) for water supply. • Forty large (>15 m) dams on every major River Murray tributary except the Ovens River by the 1970s. The largest, Dartmouth Dam (1979) built on Mitta Mitta River. Major levee systems constructed. • Trapped sediment and altered flow regimes over the entire catchment.	• Trapping of sediment in reservoirs. • Clearwater scour downstream.

Period	Human impact	Likely impacts from Yarrawonga Weir to Picnic Point
1970-Present	• Irrigation: Increasing proportion of irrigation flows and long-duration releases below Hume Dam reversed flow seasonality. Substantial flows diverted into Upper Murray from Snowy Mountains Inter-basin transfer project. High, long duration flows increase channel erosion rates from Albury to Yarrawonga. Below there, reduced discharges are main effect.	• Reduced flood peak discharges
1950s-Present	• Water skiing: Waves from water-skiing erodes banks. Entirely concentrated in summer months coinciding with long duration irrigation flows resulting in increased bank erosion along the river, especially the Tocumwal reach.	• Sediment supply increases from bank erosion.
1970s	• Carp: Introduction of invasive carp, especially spread throughout catchment from Victoria after the 1973 flood. Direct increase in mobilising suspended sediment. • Desnagging: Major desnagging (over 20,000 logs) projects between Hume Dam and Yarrawonga Weir to increase flow conveyance (Gippel *et al.* 1992). Wood removal would have increased in-channel sediment movement mostly between Hume Dam to Yarrawonga.	• Increased flux of bed sediment. • Increased instream velocities. • Channel enlargement – width and depth. • Carp mobilising sediment.

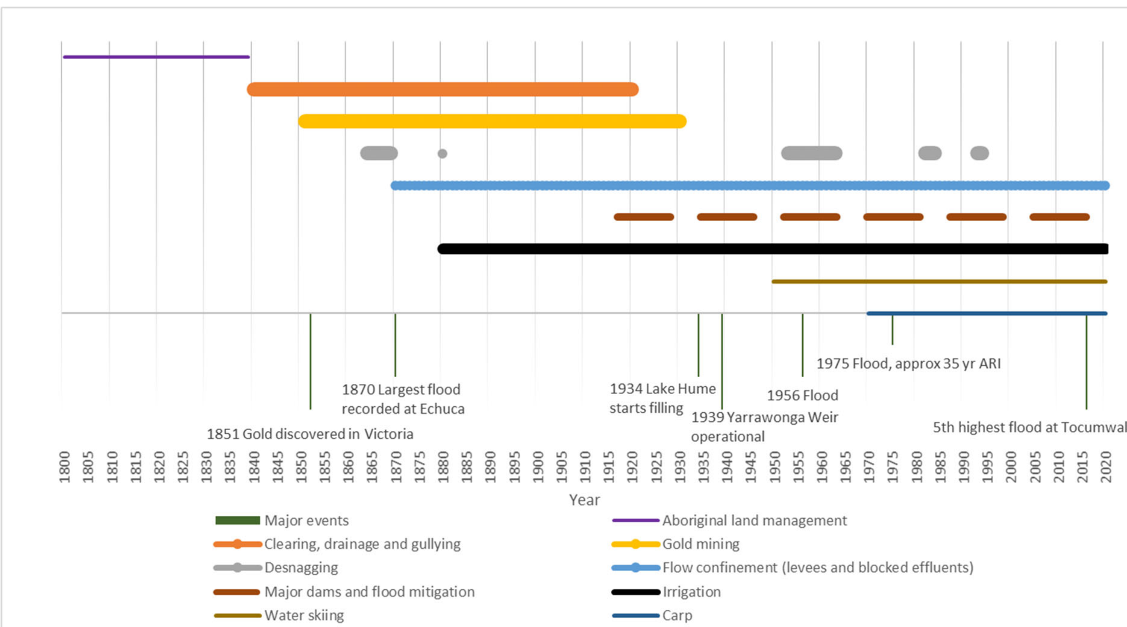

Figure E0-7. *Impacts likely to influence sediment fluxes and flow in the River Murray catchment based on data from Rutherfurd et al. (2020). The width of the solid lines indicates the likely magnitude of change whilst the dashed lines signify the disruptions in the downstream flow of sediment.*

E 6. Post-European channel changes influencing riverbed sediment from Yarrawonga Weir to Picnic Point

One of the main changes has been in the downstream flow of bed sediment. The filling of Hume Dam in 1934 and Lake Mulwala in 1939 have meant that coarse sediment transported along the bed of the River Murray since 1939 can only have been derived from downstream of Yarrawonga Weir. A review of data was, therefore, undertaken of observed geomorphic changes in the River Murray that could influence the bed sediment flux between Yarrawonga Weir and Picnic Point.

Between Yarrawonga and Bullatale Creek the meandering channel has not significantly changed in channel length, and therefore, sinuosity since the 1860's. The bankfull channel widths have on average widened by 33 m between 1976 to 1981. There was, however, very little data on the pre-disturbance sediment grainsize and stratigraphy on the riverbed and in the riverbanks.

The point bars, also referred to as beaches, were sampled in 2021 (Water Technology 2021) and were dominated by coarse sands. An analysis of all the 122 point bars visible in 1940s aerial imagery revealed that the bare sand surfaces had reduced by 27 % in 2019. This reduction was considered to be mainly the result of vegetation encroachment onto the bars rather than erosion.

Gippel and Lucas (2002) observed that downstream of Yarrawonga Weir a resistant armoured layer had developed, which they observed on point bars. They suggest that this layer was comprised of ancestral channel gravels supplied from erosion of lenses of the sediment in the riverbank. The SBP data suggested that the armoured layer extended for around 2 km downstream of the weir.

From Bullatale Creek to Picnic Point there has been limited changes in bankfull width from 1876 to 1981. The riverbanks in this reach were sampled by Water Technology (2021) and comprised of fine sands, silts and clays with less than 12 % coarse sand.

Rates of fine sediment build up on the floodplain have been estimated by Baky (2018) to have been around 2 mm in 10 years (0.0002 m/yr). However, the coarse sands building up on the riverbed have acumulated at rates of between 0.01 m/yr based on 1876-1976 surveys and 0.06 m/yr based on modelling from 1991-2020 (Gower *et al.* 2020). This means that the bed has risen at a rate of between 50 and 300 times the rate of the floodplain. Whilst the average thickness of bed sediment from Bullatale Creek to Picnic Point was 1.2 m there were larger thicknesses around effluent junctions (Gower *et al.* 2020) and up to 4.7 m in meander pools.

E 7. Possible explanations for the observed changes

Based on the history of human-induced disturbances and the data on channel changes, the following four questions were posed to help investigate the changes in bed sediment in the reach. The questions posed are arranged from the simplest to most complex combination of processes to explain the current state of sediment on the channel bed. They are:

1. Has the coarse sand bedload come from recent flooding?
2. Was regulation responsible for erosion that deposited coarse sand on the bed?
3. Did land-use change, including historical gold mining, supply the coarse sand bedload?
4. Could desnagging have increased the bedload supply of coarse sand and its mobility?

Each of these questions is explored in more detail below. For each of them, a hypothesis is put forward first to provide a basis for a subsequent evaluation of the available evidence. The arguments for and against the hypothesis are then presented, and then the current understanding of possible answers to the questions are summarised.

E 8. Has the coarse sand bedload come from recent flooding?

E 8.1. Hypothesis

A recent flood, or a period of increased flooding has been considered as a potential mode of producing some, if not all, of the sediment in the bed. These elevated discharges could both erode and mobilise sediment and may result in local sediment storage that exceeds the transport capacity of the Choke for a period of time.

E 8.2. Historic hydrology

Decadal wet and dry periods have been experienced in the River Murray. Modelling has extended the climatic record back to 1780 (Gallant and Gergis 2011), allowing a greater understanding of fluctuations in precipitation. The last major drought was the Millennium Drought between 1997 and 2010. Since 1997 the natural flow conditions have been reasonably dry, only punctuated by one major flood in 2016, which was the fifth highest daily discharge on record at Tocumwal (**Figure E 0-8**).

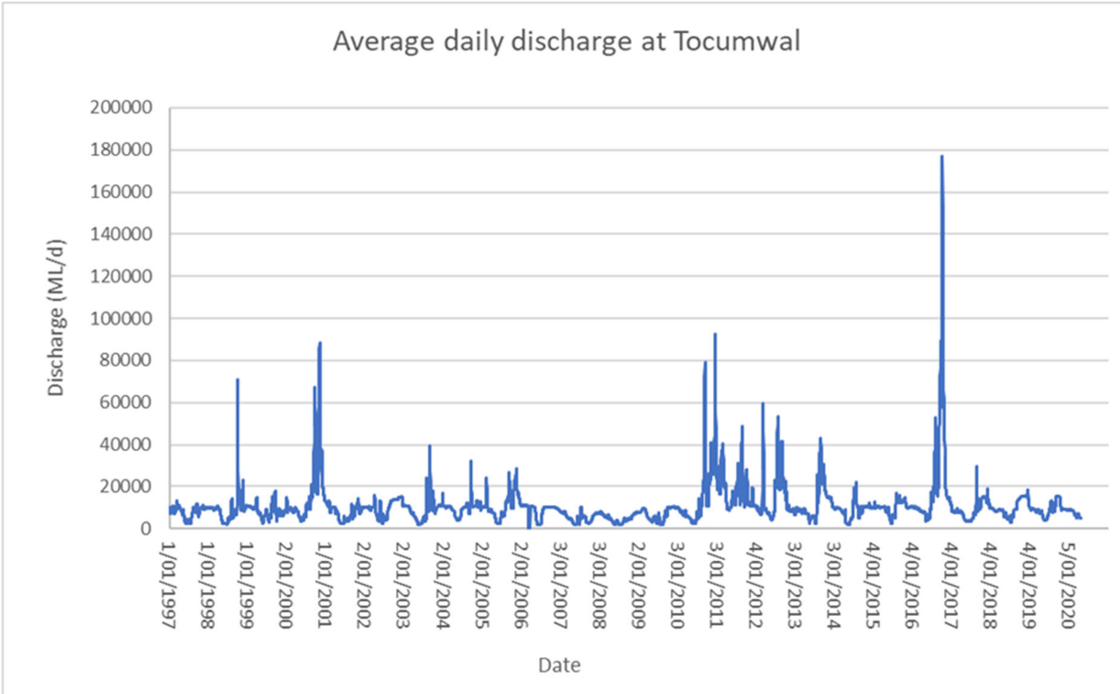

Figure E 0-8. Average daily discharge at Tocumwal from 01/12/1996 to 18/06/2020.

The effects of the 2016 flood would have been recorded in the 2017 LiDAR and 2018 Bathymetric Surveys and subsequently analysed by Water Technology (2020). However, there is little evidence reported for elevated rates of erosion based on observations of the planform sinuosity, the number of channels, the bankfull cross-sectional area, or the planform bankfull channel position.

An alternative hypothesis is that the flood could have moved existing bed sediment rather than supplying more from erosion. Recent climatic conditions appear drier than the historical record since 1780. A reduction in flooding as a result could allow a build-up of coarse sediment in the River Murray main channel between Yarrawonga Weir and Picnic Point. This is because regular flooding can lift sediment from the riverbed and deposit on the higher surfaces of point bars, the floodplain, or transport the sediment out of the reach.

The arrangement of layers in soil cores taken from the Barmah Forest suggest that since about 1954 (when radioactive Caesium 137 levels in the landscape were increased by fallout from nuclear testing in the southern hemisphere) the sediments deposited on the Barmah-Millewa floodplain consisted of finer sediments, like silts and clays, as well as fine sands (Thoms 1995). The inference is that flooding has sufficient energy to lift the finer sandy sediments up on to the floodplain in some areas but not coarser grainsizes. It is unlikely that reducing flooding led to a significant concentration of coarse sand sediments in the river channel downstream of Bulltale Creek. However, it may be responsible for increased rates of accumulation of existing coarse sand.

E 8.3. Summary

There is little evidence to suggest that recent flooding has produced more bed sediment and mobilized it to the Choke. However, it is possible that prolonged regulated flows during drier periods may be transporting the existing volume of coarse bed sediment to the downstream parts of the Barmah-Millewa system. If this were the case, it would suggest that there was already an excess of bed sediment, from some other source, that lower flows were gradually transporting to the downstream parts of the reach. The lack of flooding may have reduced the connectivity between the river and long-term sediment stores on higher elevations such as bars and possibly the floodplain – thereby reducing opportunities to move sediments out of the main channel.

E 9. Was regulation responsible for erosion that deposited coarse sand on the bed?

E 9.1. Hypothesis

The reach has been changed to allow the efficient transfer of water for downstream supply, and to reduce flooding. This has been done by:

- Constructing reservoirs and weirs,
- Artificially elevating levees along riverbanks,
- Regulating effluent streams,
- Changing the timing and stage of discharge.

All these human-induced changes have altered the amount of sediment entering the system, its conveyance along the River Murray, and its storage. These could have caused an increased load of bed sediment in the reach.

E 9.2. The influence of regulation on bed sediment

Both Lake Hume (since 1934) and Lake Mulwala (since 1939) have stopped downstream transport of bed sediments; any sediment entering these long, deep storages has settled out in the storages rather than being transported downstream. This means that since 1939 the sediment supply for Picnic Point has come only from the reach downstream of Yarrawonga Weir.

The rate of sediment accumulation in Lakes Hume and Mulwala appear to be low, with very little sediment accumulating in them since they became operational. This suggests that if any pulse of sediment was moving downstream to Picnic Point it would have had to have been downstream of Yarrawonga Weir before the weir was finished in 1939.

Levees and regulators have been constructed on effluents in this reach to prevent unseasonal wetting of the forest and to deliver water more efficiently to water users downstream. These structures reduce water losses out onto the floodplain except during flooding, but they also reduce opportunities to move sediment out of the river channel although this was not thought to be a significant volume. This means that the channel now mobilizes sediment more efficiently to downstream parts of the channel during the consistently high regulated summer flows. Regulation has also decreased flood peaks, and the net result has been a decrease in the transport of bed sediment through the Choke (Gower *et al.* 2020).

Estimates volumes of bank erosion have been made based on channel widening reported by Gippel and Lucas (2002) between 1876 and 1981, and from measurements made in this work between 1981 and 2015. Based highest percentage of coarse sand found in the riverbanks by Water Technology (2021) and the volumes of channel change, an estimated 2.3 million m^3 of coarse sand may have been eroded from the banks from Yarrawonga Weir to Picnic Point between 1876-2015. Most of the bank erosion has occurred in the more mobile channel upstream of Bullatale Creek.

In the reach immediately downstream of Yarrawonga Weir, bank erosion was likely to have been the result of a combination of factors. One of those factors is 'clearwater scour', which is common downstream of large reservoirs. Because the sediment from inflows tends to settle out in storages as water movement slows, releases from the storages have low sediment concentrations. This gives storage releases a higher capacity to erode than river water that is already carrying a high sediment load. Clearwater scour therefore typically enlarges channels downstream of storages, especially when combined with long periods of near bankfull releases from the reservoir. In this case scour has produced the armoured layer of coarse sand and gravels on the bed of the river downstream of the weir, stopping the erosion of the bed and increasing the likelihood of riverbank erosion.

Most of the channel widening was the result of disturbance after European settlement, and the associated influx of sediment during this period is not part of the natural river system. However, the 2.3 million m^3 of coarse sand supplied to the river from 1876-2015 cannot on its own account for the >20 million m^3 observed on the riverbed.

E 9.3. Summary

The construction of Hume Dam and Yarrawonga Weir has stopped the transport of bed sediment from their supply catchments to downstream reaches. Since 1939, bed sediment to the Choke can only have been supplied by the catchment downstream of Yarrawonga Weir. One of the sources of sediment during this time would be channel widening downstream of Yarrawonga Weir due to river regulation and clearwater scour. Another effect of regulation has been to reduce the transport of bed sediment through and out of the Choke resulting in greater rates of deposition. This means that there may be both an increase in coarse sand mobilized and a reduction in its transport out of the reach. Despite this, another source or sources of coarse sediment are needed to explain the majority of sediment in the riverbed.

E 10. Did land-use change, including historical gold mining, supply the coarse sand bedload?

E 10.1. Hypothesis

There have been several land-use changes that may have changed the sediment budget of the River Murray catchment (**Table E0-1**) (Rutherfurd *et al.* 2020). These land-use changes have the potential to introduce large volumes of sediment to the River Murray over a short period of time resulting in a pulse of sediment often called a 'sediment slug'. Sediment accumulation in the River Murray through the Barmah-Millewa Forest may be a result of the downstream migration of a sediment pulse.

Based on previous research, two major land-use changes have been considered as potentially large sources of bed sediment:

- Hillslope and riverbank erosion caused by vegetation and land management changes from reference conditions modelled using SedNet, and
- Inputs from historic gold mining.

E 10.2. Sediment yields from land use changes

Both land clearance and gold mining have produced high rates of sediment flow into tributaries of the River Murray. Based on modelling by SedNet (NLWRA 2011), the amount of sediment entering the Murray upstream of Picnic Point after European settlement and clearance was between 3 and 103 times greater than it was before European settlement. However, this modelling did not include the impacts of gold mining in catchments upstream of Picnic Point. This is a significant omission because Davies *et al.* (2018) estimated that between 1859 and 1891 sediment yields upstream of Picnic Point were between 20 and 256 times higher than the pre-European yields established by SedNet.

Gold mining produced sediment both by surface digging and by sub-surface excavation. The river channels were then used to process the sediment and win the gold by letting it drop out in cradles and sluice boxes. The result was an influx of both coarse and fine sediments directly into the river channels. The volumes of sediment coming mainly from upland tributaries overwhelmed the transport capacity of channels. These filled and then deposited sediment onto the floodplain, often not far downstream of the mining where the channel was no longer confined by hillslopes.

> *"Rede's Creek is so much filled that, in the property of Mr. Charlton, about four miles above Wangaratta, the old watercourse is completely obliterated by the deposit of sludge, and a new channel has been formed. The deposit reaches to the top of the old boundary fence on the property, and a further deposit occurs with every heavy rain." (Sludge Committee 1887 p. xxv)*

Once gold mining ceased, downstream channels were gradually reincised, probably from the 1890s onwards. The resultant sediment pulse may have contributed coarse sediment sizes more efficiently directly to the River Murray.

Heavy metals, which could have been sourced from historic gold mining sediments, have been sampled in Lake Hume, Lake Mulwala, the Barmah floodplain and in River Murray Locks 2 and 4. The current yields of heavy metals into Lake Hume (Baldwin *et al.* 2008) and Lake Mulwala (Baldwin and Howitt 2007) appear to be lower than historic yields, but heavy metal concentrations have been increasing in the Barmah floodplain (Thoms 1995). This suggests coarse sediment from land use change may be stored in the River Murray between Yarrawonga Weir and the Barmah-Millewa Forest, but finer sediments have largely been carried further downstream but also onto the floodplain. The coarse sands in the riverbed are unlikely to have high metal concentrations, and preliminary sampling has indicated that the heavy metal concentrations are below Victorian and NSW Environmental Protection Agency guideline values (Maher 2021).

An estimate of the bedload volume that could be sourced because of land-use changes upstream of Yarrawonga Weir, such as gullying, bank erosion and gold mining were made based on the SedNet modelling undertaken by NLWRA (2011) and the mining sediment yields modelled by Davies *et al.* (2018). The overall supply of bedload was 121.7 million m^3, not taking into account deposition, over seven times the volume of coarse sand in the river between Yarrawonga Weir and Picnic Point.

E 10.3. Summary

Since the 1840s, land clearance and gold mining have increased sediment loads upstream of Picnic Point by as much as 256 times above pre-European levels. Low rates of sediment accumulation in Lakes Hume and Mulwala show that coarse sediment must have been deposited before the construction of Yarrawonga Weir. Some of that sediment would have been deposited in long-term stores such as point bars, finer sediment would have been rapidly transported out of the reach below Yarrawonga and also onto the floodplain, and some coarse sediment may have been left on the bed.

E 11. Could desnagging have increased the bedload supply of coarse sand and its mobility?

E 11.1. Hypothesis

The removal of large wood (defined as logs greater than 1 m in length and 0.1 m diameter) from channels increases the flow velocity by reducing friction, and it decreases the cohesion of the bed. In combination these factors can lead to a higher flows of bed sediment (Erskine and Webb 2003).

There have been several desnagging operations in the River Murray, starting around 1864. These were investigated to see if they could have introduced the current excess of sediment into the Choke. The earliest desnagging efforts are likely to have caused the greatest human-induced structural changes to the river system, concentrating on those therefore provides some information on the pre-snagging conditions.

E 11.2. Changes in sediment loads caused by desnagging

Before European disturbance there would have been high loadings of large wood in the channel near the junction of the Ovens River. Surprisingly, the loads would have been significantly lower close to the Barmah Choke. This was probably because of more extensive reed beds and grasslands than there are presently in the Barmah-Millewa Forest. Aboriginal land management may explain some of this change in vegetation as burning practices took place in the forest.

For navigation purposes 767 snags were taken out of the River Murray from 7 May to 31 December 1864; in 1865 it was reported 3,903 were taken out (Parliament of South Australia 1882). In 1866 there were 3,655 snags extracted and put on the banks. It is not reported over what length of river these works were occurring, but it is calculated that 30,956 m^3 of wood was removed from the channel bed.

Wood was pulled out of the channel or cut down in-channel. Observations following this first period of desnagging recount the channel rapidly deepening even at low flows. Channel widening often occurs after deepening. If this had occurred it would probably have been greatest in the more laterally mobile part of the reach upstream of Bullatale Creek, and before the 1876 survey reported by Gippel and Lucas (2002).

Gippel and Lucas (2002) also describe the desnagging operations used to reduce channel roughness and improve flow conveyance since 1953. Between 1953 and 1963 there was a period where desnagging from Picnic Point to Barmah (i.e. 'The Narrows') also involved removing all trees within 4 m of the bank. This would have reduced the strength of the riverbank and decreased the supply of large wood to the channel. The expense of this undertaking meant that later only trees likely to fall in the river were removed. There was another phase of desnagging and willow lopping from 1976 to 1987 (Gippel and Lucas 2002). However, the exact extent of these works is unclear.

The travel distances and grain size of the mobilised sediment are unclear. Were they transported out of the reach creating whole scale channel enlargement, did the sediment redistribute slowly over the entire reach, or were there points of deposition that were long-term stores? All these probably occurred. The channel enlargement reported by Rutherfurd and Kenyon (2005) would suggest that whole scale channel enlargement did occur, but it is not possible to be confident that this was just a result of desnagging because of the other factors, already discussed, that were also occurring in this period.

E 11.3. Summary

It is evident that the channel did widen between 1876 and 2015 and this mainly occurred upstream of Bullatale Creek (Rutherfurd and Kenyon 2005). Desnagging could have been a contributor to this process. The survey in 1876 was probably after the first desnagging and the channel would therefore already have been in the process of enlargement. Hence, a proportion of the volume of sediment estimated to have been mobilized by bank erosion could have been the result of desnagging. As already noted, the bank erosion quantified is only able to supply a small proportion of the sediment in the reach and so desnagging can only be a small contributor to the current bedload. A more likely effect of the desnagging would have been to change the transport efficiency of sediment on the bed, and perhaps increasing the transport of coarse sand towards the Choke.

E 12. Conclusions

Recent surveys of the River Murray channel through the Barmah-Millewa Forest revealed much larger volumes of coarse sand in the bed of the channel than would be expected for a river having similar characteristics in terms of physical forms and processes. The sediments deposited in otherwise deep pools on meander bends, and the dune forms of sand on the bed, are both evidence that the sediment loads are much greater than would be expected under natural conditions. For the 190 km reach from Yarrawonga Weir to Picnic Point, the volume of coarse sand has been estimated as being greater than 20 million m^3.

There are two main questions facing river managers:

1. What is the source of this excess sediment? Has it been derived naturally and is it part of the normal variability in the channel, or is it derived from human activities? Knowing the answer to this question could provide scope to deal with the sediment supply using targeted approaches.

2. What is the likely trajectory of the sediment in this reach over time? Will the excess sediment rapidly pass through the reach with minimal intervention required, or will this be a prolonged issue that requires active management?

With regard to the first question, this work suggests that the excess sediment is predominantly a result of post-European human disturbance. The conclusion is based on the following main points:

- The pre-European reference channel was narrower upstream of Bullatale Creek, had higher flood peaks, and less coarse sand-sized bed sediment.

- Catchment disturbances upstream of Picnic Point from gold mining and land clearance, that caused gullying and bank erosion, mobilized sediment at up to 256 times the pre-disturbance volumes. The estimated bedload produced between 1859-1891 was over seven times the mobile bedload between Yarrawonga Weir and Picnic Point (**Table E0-2**).

- The major storages (Hume and Mulwala) have cut off the upstream supply of bedload sediment since 1939. However, desnagging and river regulation have mobilized sediment locally in the channel since that time. This local erosion from bank and point bar erosion could account for approximately

3.7 million m³ of the >20 million m³ of coarse sand in the bed (**Table E0-2**) it would, however, add to any sediment mobilized from upstream before 1939.

Table E0-2. *Estimated volumes of coarse sediment mobilized into the reach between the current location of Yarrawonga Weir and Picnic Point.*

Source of coarse sand	Volume of coarse sediment (million m³)
Upstream gold mining	124.8
Upstream land clearance: bank erosion and gullying	16.9
Bank erosion within the reach	2.3
Bar erosion within the reach	1.4

Returning to the second question, there is a high probability that the trajectory for sediment transport through the Barmah-Millewa Forest will be a long-term issue. The reach downstream of Yarrawonga Weir has a large store of sediment, which manifests as deep bed sediments and mobile dunes. This sediment, already stored in the channel, is migrating downstream. The lack of large wood in the reach means that storage on the bed is more limited and transport downstream is slow but effective.

The loss of channel capacity through the Barmah-Millewa Forest is likely to be due to the build-up of sediment. The loss of flow to effluents downstream of Bullatale Creek means that aggradation in the downstream parts of the reach result in the build-up of bedload there from sediments that have been transported from the upstream parts of the reach. The bifurcation points, where effluent streams leave the main channel, are characterised by high sediment deposits in the main channel immediately downstream of the offtake (Gower *et al.* 2020). Rates of up to 1.9 m of sediment accumulation between 1991-2020 have been modelled by Gower *et al.* (2020) based on the discharges during that time.

E 13. Prediction for the next 10 years

There is a very large sediment store of coarse sand in the reach of the River Murray between Yarrawonga Weir and Picnic Point. The total volume of sediment has been estimated as >20 million m³.

The sediment is continuing to move downstream, and in the absence of major floods it is unlikely that any significant quantity will be lifted out of the channel and onto point bars for storage. Based on observations of the historic aerial photos, specific gauge records, and SBP, it is apparent that sediment stores have started to decline in the upstream sections of the reach, as the sediment moves downstream. The sediment will continue to clear in the upstream section of the reach, but the cross-sectional surveys at the Yarrawonga Weir and Tocumwal gauges suggests this will happen very slowly. If the same rates were maintained for the next decade then there would be between 0.05 - 0.1 m of average bed lowering. Over the next ten years the bed is likely to lower over 10s of kilometres downstream of Yarrawonga Weir and it is not expected to lower just upstream of Bullatale Creek for many decades.

Based on measured historic rates of accumulation and the more recent modelled rates the bed between Bullatale Creek and Picnic Point may build up between 0.1 – 0.6 m in the next decade without any intervention. The rates could be higher if there is a period of increased flooding. As the channel decreases in depth the risk of channel avulsion will increase as will the potential for increased bank erosion.

It is expected that without any management there will be continued fluctuations in bed levels, with more extended periods of reduced capacity to deliver water through the Choke, for several decades. There would also be increased rates of bank erosion as the channel widens to accommodate the reduced depths. In the worst-case scenario, aggradation could cause sediments to build-up in the channel through the Barmah-Millewa Forest to a point where an avulsion creates a new channel or reoccupies and old channel to bypass the Choke.

E 14. Suggestions for further work to improve confidence

- Hydraulic modelling to estimate the likely rates and volumes of bed sediment flux between Yarrawonga and Bullatale Creek.
- Observations on erosion and sediment transport in effluents.
- Observations of sand sediment deposition on the floodplains of the Barmah-Millewa Forest, such as cores that show any changes over time.
- Measurements of aggradation rates and changes in chemical composition in Lake Mulwala, like that undertaken by Baldwin *et.al* (2008) in Lake Hume.
- A quantification of the riverbank sediment composition from Yarrawonga Weir to Bullatale Creek alongside bed particle size analysis in the same reach.

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1 Introduction

1.1 Problem Statement

The Barmah Choke section of the River Murray has a naturally small cross-sectional area. This constriction controls the volume of flows that can be delivered downstream by river operators. The channel capacity through the Choke appears to be reducing leading to concerns about the continued reduction in the water volumes that can be released from Yarrawonga Weir. Volumes released have had to be reduced so they do not go out of the channel and into the Barmah-Millewa Forest. The decrease in channel capacity could be explained by several factors, but recent bathymetric survey alongside the quantification of bed sediment size and volumes indicates infilling of the bed by coarse sand could be a factor.

This study investigates the geomorphic and hydrological processes that could influence flow capacity and sediment transport through the Choke. It then outlines the history of different sediment sources and whether they may be responsible for the volume of sand on the riverbed. The aim is to determine if the large volume of sediment observed is likely to be the product of natural or anthropogenic causes. Finally, it will assess whether channel capacity changes are likely to occur over short or long timescales.

1.2 Report Structure

This report will outline the current regulated operations of the Barmah Choke to set context. Data will be presented that has allowed the volume and grainsize of the riverbed from Yarrawonga Weir to Barmah township to be quantified. Some of the major historical anthropogenic modifications to the River Murray that influence the Choke will be briefly outlined. The extent of the river to be used in this study will be described alongside the geomorphic stream type, and its likely reference bed sediment.

Based on the history of human-induced disturbances and the data on channel changes, the following four questions will be posed to help investigate the changes in bed sediment in the reach. The questions have been arranged from the simplest to most complex combination of processes to explain the current state of sediment on the channel bed. They are:

1. Has the coarse sand bedload come from recent flooding?

2. Was regulation responsible for erosion that deposited coarse sand on the bed?

3. Did land-use change, including historical gold mining, supply the coarse sand bedload?

4. Could desnagging have increased the bedload supply of coarse sand and its mobility?

For each question, the factors that influence coarse sand input to the bed and its transport will be discussed. The volumes of sand from different sources will then be collated to indicate likely sources and volumes of the current coarse sand on the riverbed.

1.3 Scoping the current ability of the Choke to convey flow

1.3.1 The location and operation of the Choke

The Barmah Choke is on the River Murray between Tocumwal and Echuca. This reach has the lowest regulated channel capacity on the River Murray between Lake Hume and South Australia (Ladson and Chong 2005) (**Figure 1-1**). The Choke may be considered three different constriction points, the Tocumwal Choke, the Barmah Choke and the Edward Choke. Gower *et al.* (2020) define the Choke as beginning around Bullatale Creek, 26 km downstream of Tocumwal, and extending as far as Barmah township. Discharges allowed through the Choke are set using the data from the gauge at Picnic Point. In this report the gauge will be a point of major consideration when looking at changes in channel capacity.

The river flows upstream of the Choke, and its surrounding Barmah-Millewa Ramsar listed wetland, are released from Yarrawonga Weir. River flows during the irrigation season are designed to maximise flows through the Choke and minimise flooding of the wetland.

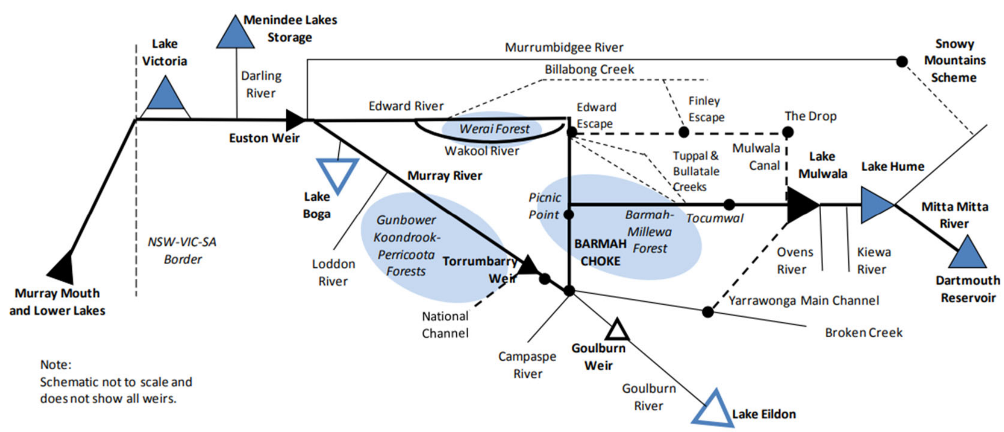

Figure 1-1. *A schematic representation of the River Murray system (SKM 2012)*

In 2011, when a flow of 10,600 ML/d was released through Yarrawonga Weir, 8,500 ML/d passed through the Choke and 2,100 ML/d was sent along the distributaries of the Edward River and Gulpa Creek (Ecological Associates and SKM 2011) (**Figure 1-2**). This can be considered to have been the maximum operational capacity of the Choke. In 2019, the figure quoted for flows allowed through the Choke at Picnic Point to stop overbank flooding was only 7,000 ML/d (Water Technology 2020). Below 7,000 ML/d it was suggested that some minor effluent creeks may have taken water. Thus, between 2011 and 2019 there appears to have been a reduction of 1,500 ML/d in the volume of water that can be sent through the Choke before it spills into the Barmah-Millewa Forest.

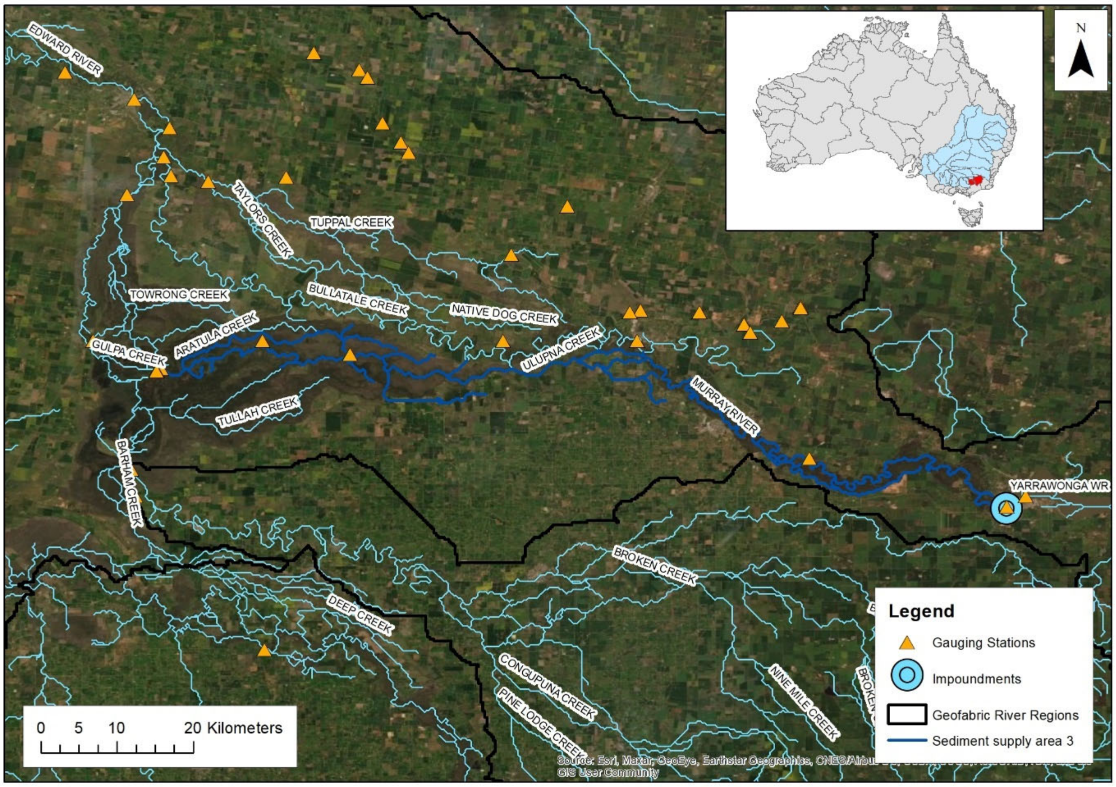

Figure 1-2. A map of the River Murray between Yarrawonga Weir and Picnic Point using BOM (2020) data, flow is from left to right in the image.

1.3.2 An overview of the geomorphic setting of the Barmah Choke

In order to put these changes in capacity at the Choke in context its formation and geomorphic processes need to be understood. The ancestral course of the Murray was disrupted by the Cadell Fault that runs in a north-south orientation between Deniliquin and Echuca. This caused the River Murray to shift position into what is now Gulpa Creek, then it switched and flowed along what is now Bullatale Creek. During these periods the channel flowed further north than it does presently. The River Murray diverted south along the Cadell Fault about 8,000 years ago (Gippel and Lucas 2002) flowing towards Echuca.

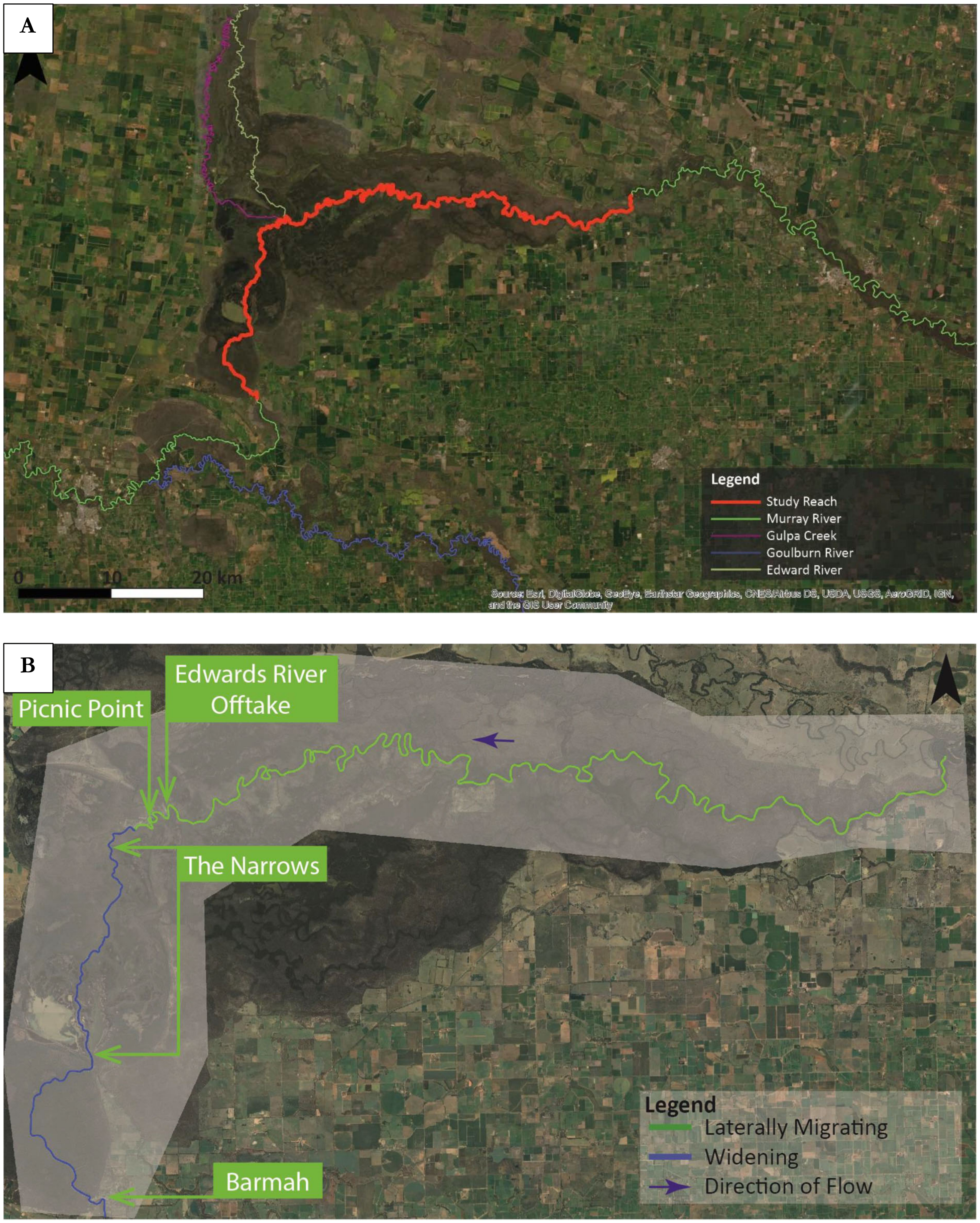

Figure 1-3. *A) The reach extent used by Water Technology (2020) to investigate channel changes, B) the dominant process zones identified in the reach by Water Technology (2020).*

The current channel that has resulted from these historical changes can be divided into three distinct reaches (Rutherfurd and Kenyon 2005) with River Murray chainages shown:

1. Corowa (2080 km) to Bullatale Creek (1862 km), bankfull capacity of around 25,000 ML/d.

2. Bullatale Creek (1862 km) to Picnic Point (1790 km), bankfull capacity decreases downstream to 8,500 ML/d at Picnic Point.

3. Picnic Point (1790 km) to Bama Sandhill (1750 km) which is approximately 8 km downstream of Barmah township (1762 km), bankfull capacity increases downstream to a major flood capacity of 35,000 ML/d.

Between Corowa and Bullatale Creek the river is relatively wide set in a narrow floodplain of around 3 km in width. The meandering channel has distinctive and extensive sandy point bars. Further downstream, Tuppal and Bullatale Creeks are large effluent channels that take water from the River Murray and deliver it to the Edward-Wakool system (**Figure 1-3**).

Downstream of Bullatale Creek and extending to the Cadell Fault a triangle shaped alluvial fan provides the geomorphic setting for the Barmah-Milawa Forest. Once the river enters the forest on this fan it decreases in sinuosity, sandy point bars disappear, silty-clay levees appear, and the bankfull width decreases (Rutherfurd and Kenyon 2005). This section of river is known as 'The Narrows' and this is the area that acts as a constriction to regulated flows. The forest is a network of effluent channels that at high stages take flows from the Murray and distributes them over the forest. These effluents have had regulators constructed on them at various times, from basic wood structures to engineered gate structures with greater flow control. The building of the regulators was finalised in 1959, controlling flows out of the River Murray and into the forest (**Figure 1-4**).

Downstream of Picnic Point the channel crosses over ancient lake beds and receives flows from the re-joining of upstream effluents. The result is a low sinuosity channel that is wider and shallower than upstream.

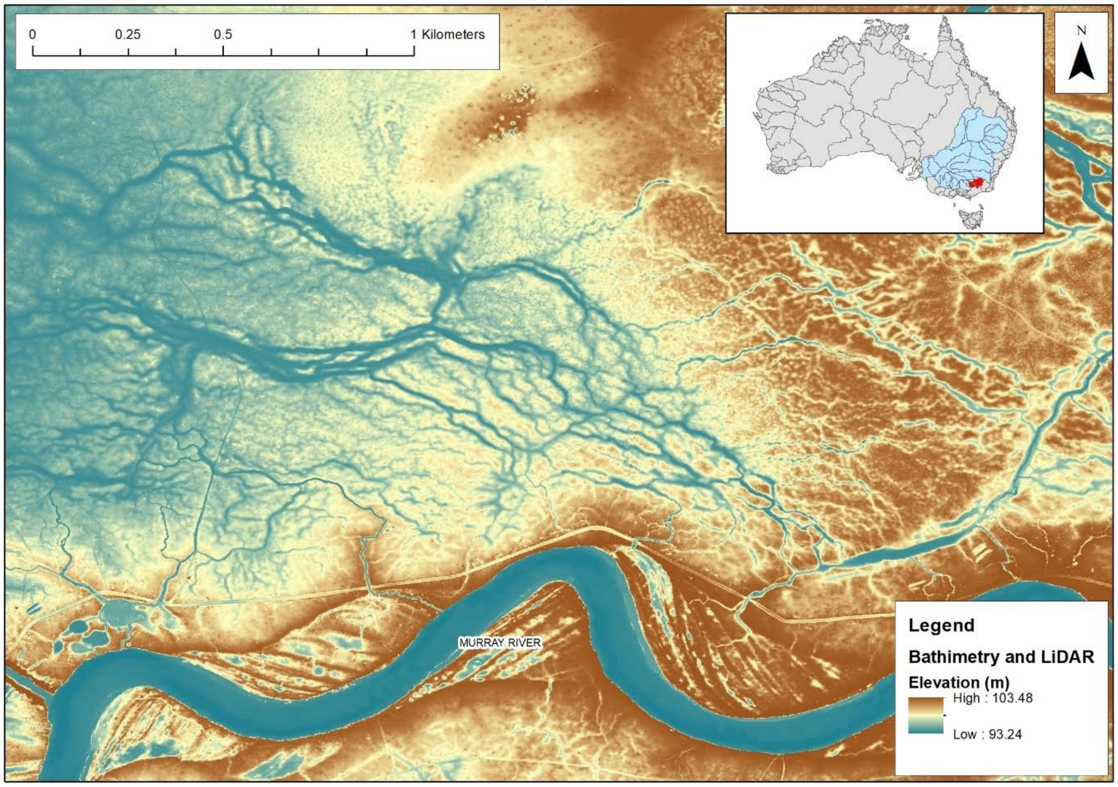

Figure 1-4. *An example of the network of effluent channels out into the Barmah-Milawa Forest, flow is from right to left in the image.*

The flows in the River Murray are now highly regulated. A balance needs to be maintained between the volumetric needs of the downstream users, storage volumes and the discharges in the channel. In some circumstances a rainfall rejection flood may occur where there is predicted to be an excess volume in Lake Mulwala. These rainfall rejection flood events are one of the times that regulators may be opened in the forest effluent channels (**Table 1-1**). At flows between 10,400 and 16,000 ML/d, channels, swamps and other low-lying areas, including about 16 % of the forest, can be inundated.

Table 1-1. *Barmah-Millewa Forest regulator capacities (Ecological Associates and SKM 2011 p.31)*

Regulator Name	Wetland/creek system	State	River Murray Q needed to commence to flow (ML/d)	Capacity at low River Murray flows (ML/d)
Mary Ada	Toupna Creek	NSW	3,500	2,800
House Creek	House Creek	NSW	6,000	630
Pinchgut Creek	Pinchgut Creek	NSW	4,500	375
Nestrons	Douglas Swamp	NSW	4,500	240
Walthours	Walthours Wetland	NSW	4,500	90
N/A	Duck Lagoon	NSW	~4,700 to provide Gulpa Ck flow of 400	Unknown
N/A	Reed Bed North Wetland	NSW	~4,500 to provide Gulpa Ck flow of 370	Unknown
N/A	Reed Bed South Wetland	NSW	~4,500 to provide Gulpa Ck flow of 370	Unknown
Horse-shoe Lagoon	Horse-shoe Lagoon	NSW	Unknown	Unknown
Crumps	St. Helena	NSW	Unknown	Unknown
Black Swamp	Black Swamp	NSW	Unknown	Unknown
Sandpit Regulator	Smiths Creek	VIC	9,000	340
Gulf Regulators	Gulf Creek	VIC	3,000	2,400
Stewarts Kitchen	Unknown	VIC	9,000	20
Bull Paddock	Unknown	VIC	9,000	40
Punt Paddock Creek	Unknown	VIC	8,000	90
Big Woodcutter Creek	Unknown	VIC	7,500	90
Boals Creek	Boals Creek	VIC	5,000	90
Sapling Creek	Sapling Creek	VIC	7,500	40
Island Creek	Island Creek	VIC	7,500	40

The capacity of the Choke has been determined by comparing the discharge gauged at Tocumwal and the stage at Picnic Point. Gippel and Lucas (2002) have described three main capacity phases since 1992:

1. 1992-1997 was a gradual loss of capacity resulting in reduced discharges from Yarrawonga Weir to stop overtopping of the banks at Picnic Point.

2. 1998-2001 was a period of increased Choke capacity.

3. 2001-2002 declining Choke capacity.

They suggested that the observations could not easily be explained; however, if hydraulically important points in the Choke are blocked by shifting bedforms or snags then capacity changes could result.

The MDBA (2009) investigation into the Barmah Choke capacity between 1980 and 2006, using a similar analysis to Gippel and Lucas (2002) identified two regulated release levels from Yarrawonga Weir Downstream before 1995/96. These were Level A operating periods with releases of around 10,600 ML/d and Level B releases of between 11,000 and 11,700 ML/d. The higher, Level B, releases ceased in the 1995/96 period.

Their findings for the Level A releases were that the capacity of the channel at Picnic Point has remained 'relatively constant over time' between 1980 and 2006. However, there was a 0.02 m reduction in gauged levels being delivered to Picnic Point from an average operating level of 2.59 to 2.57 m. Discharges from Yarrawonga Weir decreased by 700 ML/d from 11,300 to 10,600 ML/d. The changes are summarised in **Figure 1-5**.

Operating changes were concluded by MDBA (2009) to be the result of:

1. A reduction in the capacity of the Edward River offtake.
2. The Yarrawonga Weir 1980/81 rating table had changed, and lower water levels were needed to maintain a constant downstream flow. This was probably because of incision of the channel at the Yarrawonga Weir Downstream gauge.

No evidence was found for a general decline in hydraulic capacity through the Choke and they predicted this to stay the same into the future.

For this report, 2019/2020 data has been added to the findings of MDBA (2009) (**Figure 1-5**). These data show that rather than staying similar to 2005/2006 values there has been a continued decline with releases from Yarrawonga Weir further declining by 1,400 ML/d since 1995/1996, resulting in a total reduction of 2,100 ML/d from the early 1980s.

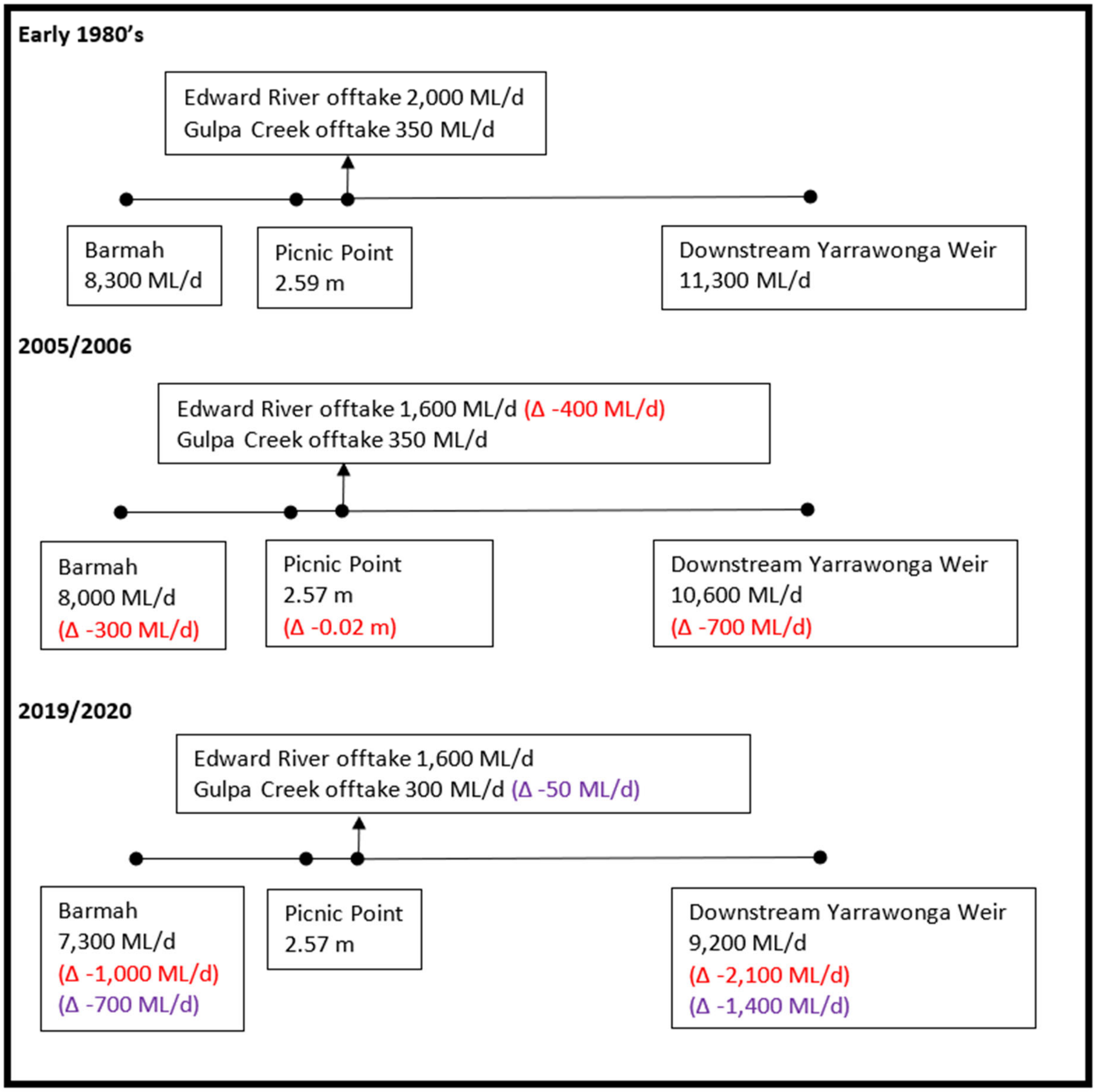

Figure 1-5. *Step change in operating flow at Yarrawonga (early 1980s to 2019), adapted from MDBA (2009). The red coloured text indicates changes from the 1980s whilst the purple text shows changes since 2005/2006.*

The issue of reduced channel capacity in the Barmah Choke was revisited in 2019 by Water Technology (2020). This was because a combination of data sources suggested that releases had to be reduced from 10,600 ML/d in 1996 to below 9,500 ML/d downstream of Yarrawonga Weir in 2019 to stop overbank flows in the Choke. There were also concerns that the erosion of riverbanks and levees was occurring at the same time as the reduced channel capacity, unseasonably inundating the Barmah-Millewa Forest. The reach shown in **Figure 1-3A** was studied for changes in channel cross-sections. Despite limitations in the number and position of repeat cross-sectional surveys Water Technology (2020) concluded that there was *"some indication of minor channel capacity reduction occurring in the upstream reaches"*. These were in River Murray chainages between 1860 and 1795 km, so from just downstream of Bullatale Creek to just upstream of Picnic Point.

Based on 2001 and 2016 LiDAR captures and channel bathymetric data from 2018, Water Technology (2020) were able to undertake further analyses of channel capacity not possible by MDBA (2009). They found that:

1. Bankfull channel widths have slightly increased in the section of the Choke known as 'The Narrows' (**Figure 1-3B**) from 2001-2016.
2. The channel bed elevation appears to have stayed the same in The Narrows meaning the channel cross-sectional area is probably not decreasing.
3. Bankfull channel widths in the upper reach, at the upstream end of the Barmah-Millewa Forest (**Figure 1-3**) have not changed significantly from 2001-2016.
4. The hydraulic conveyance loss is likely to be the result of the erosion and breaching of levee features, resulting in increased water losses in the forest.

They noted that, based on the available data, that they could not state with confidence that the channel capacity was decreasing to a point where it may eventually reduce the ability to convey regulated releases downstream. The study did note that the bed was dominated by coarse sands and that this may have infilled pools and buried large woody debris.

1.3.3 The estimated volume of bed sediment from Yarrawonga Weir to Picnic Point.

In a river system there are three main components of sediment transport (**Figure 1-6**):

1. **Bedload:** the sediment that either rolls, slides or takes small jumps (saltates) along the riverbed. The mobile sediment is usually either in contact or under a couple of particle diameters away from the bed.
2. **Suspended load:** those particles that have turbulent forces that overcome the gravitational force on the particle can remain in suspension for long distances. If the shear stress increases on the bed, such as during a flood, some particles may move from being transported on the bed to going into the suspended load.
3. **Wash load:** those particles that remain in suspension. These are usually fine particles silt-clay sizes that have low settling velocities. This means that they remain in near-permanent suspension.

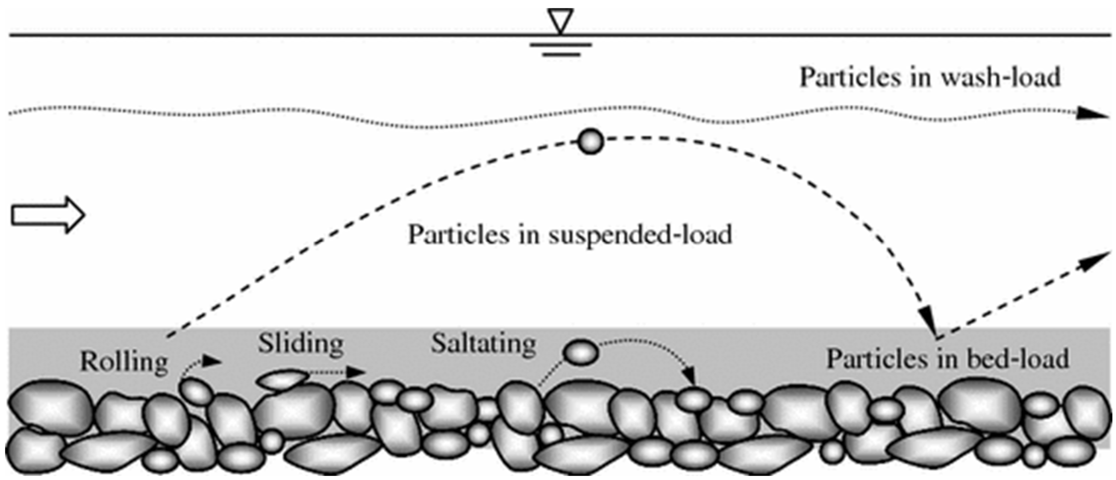

Figure 1-6. A schematic of different types of sediment transport in a river (Dey 2014)

The suspended and wash loads can be measured using sampling techniques, such as suspended sediment samplers that take a water sample. The turbidity of the water can be measured as a proxy for the sediment load. Bedload sampling can also be undertaken but often requires equipment either to be placed or inserted on the bed to trap sediment so measure how much sediment is moving over time. These sampling techniques are much less frequently undertaken than those for the suspended load. As a result, our understanding of the volumes and timing of bed sediment transport is poorer than that for the suspended load.

To investigate the volume of sediment in the bed of the River Murray, and provide further evidence on pool infilling, a sub-bottom profiler (SBP) was used. The SBP uses a boat mounted acoustic emitter and receiver to send pulses of soundwaves into bed and then detecting the soundwaves that are reflected. These data can inform on the density of sediment in the riverbed, with bedload sediment often being less dense than the underlying riverbed base. The reflector signals were used to identify the depth of the bed material which they defined as "*a sporadically transported unit consisting of larger sediment grain sizes. Bedload remains in almost continuous contact with the bottom, and moves by rolling, skipping, or sliding along the bottom*" (SA Water 2020 p. 4).

A preliminary survey was undertaken using a sub-bottom profiler (SBP) (SA Water 2020) (**Figure 1-7 to Figure 1-10**). Over the 24 km extent of the pilot 2020 SBP data (**Figure 1-7**) the average mobile bed sediment depth was 1.09 m, however, there were accumulations of over 4 m in depth. These data showed that the outside of meander bends that would normally be expected to have a deep pool were filled with sediment.

Surface bed sediment has been sampled by Water Technology (2020) and was found to be coarse to medium sand. The presence of deep sand with dune forms in what would normally be deeper bends (**Figure 1-9**) suggests that they have filled with sand. The cross-section also indicates that there is a relatively symmetrical shape with no marked deepening against the outer bank on the right-hand side of the cross-section, suggesting a sheet of sand. In straighter sections the SBP recorded dunes with a crest-to-crest length of 30-50 m and heights of 0.5-1 m, again, suggesting higher than expected loads of mobile sediment.

There were no data to suggest the depths of bed sediment in the reach that would have occurred in a pre-regulation reference condition. It cannot, however, be assumed that there was no bed sediment in pre-European conditions. Some of the SBP measured sediment could be from the pre-disturbance channel. However, the sediment depths, bedforms, particle sizes and loss of pool capacity all pointed to an excess of bed sediment for the reach surveyed. The accumulation of this sediment within the Barmah Choke would have the potential to reduce the channel capacity.

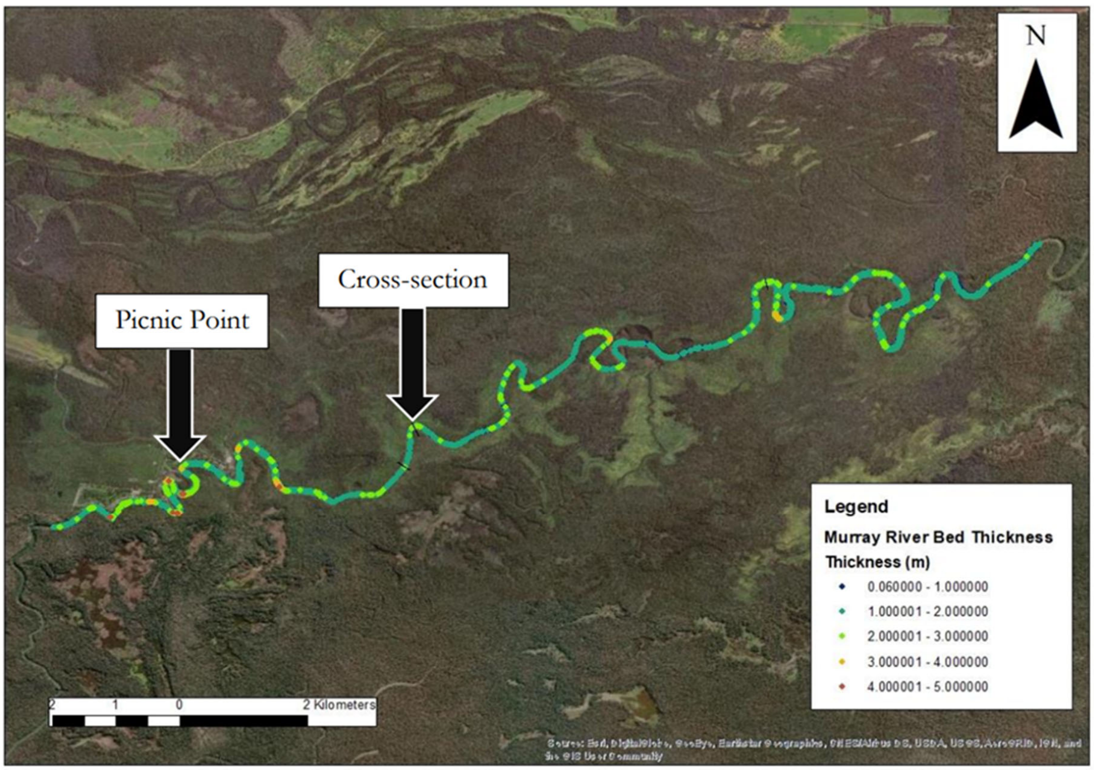

Figure 1-7. *The extent of the 24 km pilot sub-bottom profiler survey undertaken in 2020, the bed sediment thicknesses are shown by classifying them into 1 m intervals. Picnic Point is near the western end of the surveyed reach and the cross-section in **Figure 1-9** is labelled (SA Water 2020). Flow is from right to left in the image.*

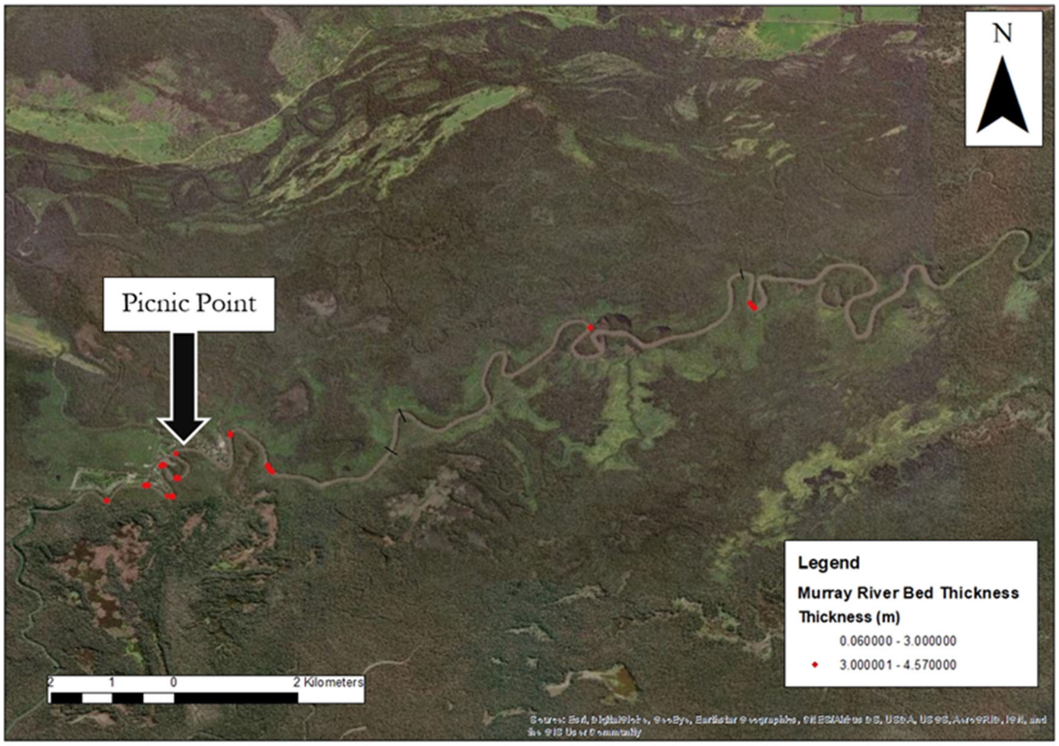

Figure 1-8. *The extent of the SA (2020) SBP survey with depths over 3 m shown. Picnic Point is near the western end of the surveyed reach.*

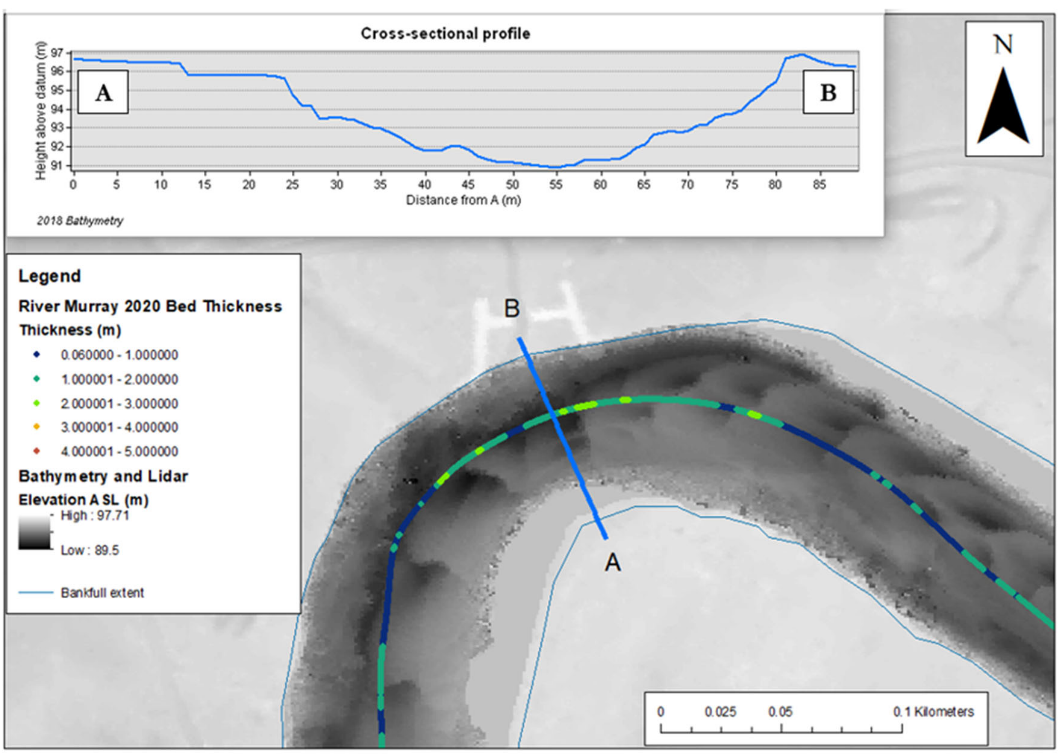

Figure 1-9. *Cross-section of meander bend showing depths based on 2018 bathymetry. Flow is from right to left of the image and the cross-section starts at A and finishes at B. In-channel the lighter colours indicate the crests of the dunes and the darker colours their troughs. The thickness of bed sediment captured in 2020 are shown by the coloured river centreline.*

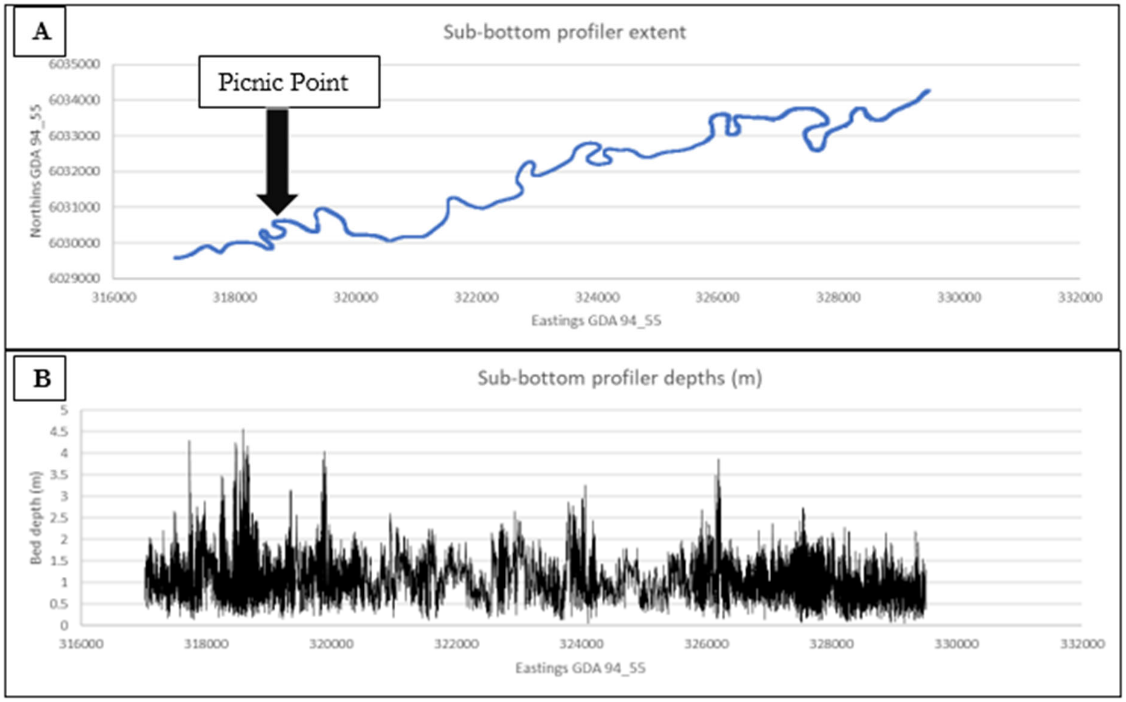

Figure 1-10. A) The planform of the SBP extent, B). SBP depths of sediment on the bed in metres (SA Water 2020)

A further set of SBP measurements were undertaken in 2021 (SA Water 2021a; 2021b) to determine if the high bed sediment loads were more extensive. Measurements were taken from Yarrawonga Weir to Nine Panel Creek in March 2021 and from Picnic Point to Barmah township in June 2021 (**Figure 1-11**). These data confirm and extend the findings of the original 2020 SBP survey. Combining the 2020 and 2021 data showed an average bed sediment depth of 1.22 m from Yarrawonga Weir to Picnic Point (**Appendix A1.4**).

Sediment depths were also manually sampled by Water Technology (2021) to verify the SBP data, and more samples were collected to determine bed sediment sizes. There was no significant difference between the SBP and the manually measured depths, indicating that the SBP depths are accurate. The mobile bed sediment composition was around 95 % coarse sand and less than 1% silts and clays whilst beneath the mobile sediment the sediment was predominantly silt and clay.

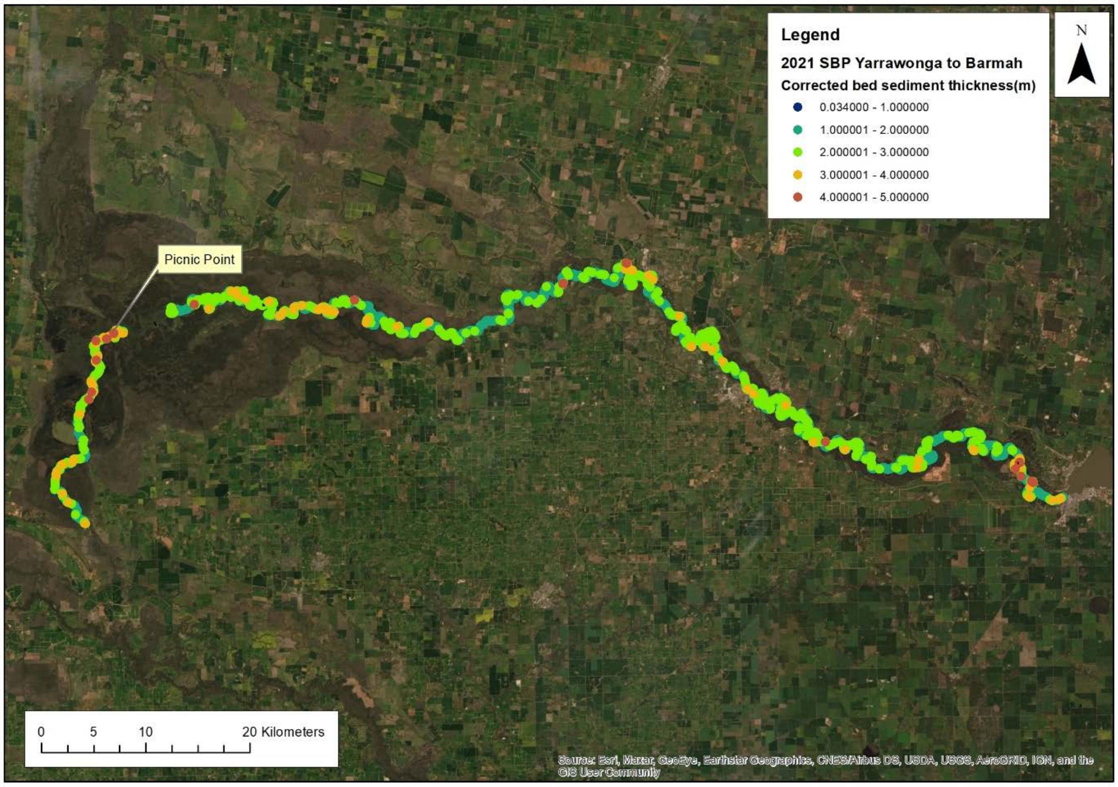

Figure 1-11. *The extent and depths of SBP measurements undertaken in March and June 2021 (SA Water 2021a; 2021b).*

Understanding the volume of coarse sand in the bed of the River Murray allows the volume of potential coarse sand sources to be estimated and compared. The riverbed was delineated using the extent of the water surface and this used to calculate the surface area (**Appendix A1.4**). The bed was divided into 10 km reaches and the volume of sediment in each of the 19 reaches between Yarrawonga Weir and Picnic Point was calculated using the area and average SBP depth. The total volume of coarse sand in the riverbed between Yarrawonga Weir and Picnic Point was estimated to be around 23 million m^3, however, to account for any errors in quantification it will reported as >20 million m^3 (**Appendix A1.4**).

To understand the current state of bed sediment the geomorphic character of the river must be determined to suggest a range of expected or reference processes and forms. This report investigates the expected bed sediment sizes, volumes, and fluxes. Historic changes to the catchment will then be investigated to decide if they may have altered both the channel form and fluxes of sediment to result in the large volume of coarse sand identified between Yarrawonga Weir and Picnic Point. Understanding the catchment history alongside the current forms and processes will allow the future trajectory of the Barmah Choke to be predicted.

Table 1-2. Summary Box 1

- Regulated flows out of Yarrawonga Weir have reduced from 10,600 ML/d in 1996 to below 9,500 ML/d in 2019. These changes correspond with a reduction in flows passed through the Choke from 8,300 to 7,300 ML/d for the same period.
- Several previous studies have come up with conflicting conclusions about a capacity change through the Choke. Gippel and Lucas (2002) suggested the Choke capacity decreased from 1992-1997, increased until 2001, then was declining in 2002. They suggest these capacity changes could be the result of shifting bedforms or snags.
- MDBA (2009) found little evidence for a capacity change at the Choke and indicated that it was more likely to be the result of a reduction in the Edward River offtake capacity, and a rating table change at Yarrawonga Weir.
- Water Technology (2020) found little evidence for changes in channel cross-sectional areas. This was before data was available on mobile sediment depths on the bed. They suggested that a reduction in the regulated discharges able to be transferred through the Choke could be the result of the erosion and breaching of levee features.
- The recent sub-bottom profiler data from SA Water (2020; 2021a; 2021b) has shown an accumulation of bed sediment from Yarrawonga to Picnic Point and this concurs with 2018 bathymetric data that meander pools were full of sediment.
- **It appears that the estimated >20 million m^3 of bed sediment that mainly comprises coarse sand was greater than expected, based on the loss of pool capacity and bed dune heights. The reduced channel capacity at the Choke is likely due to this excess sediment.**

2 Historic anthropogenic changes to the River Murray

The River Murray has been altered anthropogenically over many centuries. The extent and timing of changes to the river system need to be understood to understand if anthropogenic modification were responsible to for some, or all, of the coarse sand in the bed of the river. Rutherfurd *et al.* (2020) reviewed the history of human impacts on finer particle size suspended sediment in the River Murray and divided the chronology of impact into four periods:

1. Aboriginal period (before 1840)
2. The gold and gully period (1850s–1930s)
3. Hiatus period (1930s–1960s)
4. Regulation period (1960s–Present).

These periods contain several different changes to the sediment and flow in the River Murray (**Table 2-1**) (**Figure 2-1**). The anthropogenic alterations to the River Murray catchment may be considered: local, such as the building of Lake Mulwala; catchment wide, such as land clearance; or multiple, such as desnagging. However, all these examples can influence bed sediment fluxes over long distances in the river channel.

Some alterations have changed the volume of sediment that has been mobilized to the River Murray channel as bedload, such as land clearance, and gold mining. Other changes have influenced the mobility of bed sediment, for example river regulation or desnagging. It is important to understand both these changes in the catchments upstream of the Choke. However, changes in the mobility of sediment would have had a much greater effect in combination with an increase in sediment available for transport. It is, therefore, important to evaluate the magnitude and sources of increased bedload supply. These changes will be explored in more detail throughout the report.

The combination of changes to sediment supply and hydrology, especially in the last 150 years, means that there are many reasons to indicate anthropogenic alterations to the bed sediment at the Choke. To evaluate the impact of these changes on the flow capacity of the Choke the geomorphology of the system needs to be understood, any change in the contributing area of bed sediment evaluated, and likely sources of bed sediment estimated along with their volumes.

***Table 2-1**. Human impacts in the River Murray adapted from Rutherfurd et al. (2020)*

Period	Human impact	Likely impacts from Yarrawonga Weir to Picnic Point
Aboriginal	• Fire: Changed land cover over millennia.	• Potential for minor alterations in catchment runoff and hydrology.
Post-1840s	• Fire regimes changed in frequency, intensity, and season. • Increase in erosion rate throughout the Murray-Darling Basin.	• Potential for slightly higher sediment yields.
1840s-1920s	• Clearing, drainage and gullying: European squatters, introduction of sheep and cattle. Coincident with gold mining, population expansion, agriculture, forest clearing, swamp, and floodplain drainage. • Increase in erosion and sediment mobilization throughout the Murray-Darling Basin.	• Decreased surface roughness, reduced evapotranspiration, resulting in higher hillslope runoff causing gullying and sheet erosion. • Increased sediment mobilization into the channel alongside increased discharge.
1851-1930	• Gold mining: quickly spreads throughout the basin by 1860. • Huge increase in sediment supply mainly from the southern basin—Upper Murray, Kiewa, Ovens, Loddon, Campaspe Rivers.	• Change in the timing and volume of flows due to mining operations. • Increase in the sediment supply from tributaries.
1864-1869	• Desnagging: River Murray between Albury and Echuca >3,000 large snags were removed. Wood removal would have increased in-channel sediment movement throughout the river length.	• Increased flux of bed sediment. • Increased instream velocities. • Channel enlargement – width and depth.
1870-1898	• Flow confinement: Effluent channels blocked; flood levees constructed especially after 1870 Great Flood. By 1898 Echuca to Swan Hill works blocked floodwaters on Victoria side to maintain freshwater lakes. • Flow concentrated in channel, increase sediment transport, reduces water losses to floodplain.	• Increase in channel velocities resulting in a greater flux of bed sediment. • Reduced sediment deposition onto the floodplain.
1880	• Desnagging: River Murray was cleared of the largest logs (Trueman 2011). Wood removal would have increased in-channel sediment movement. Throughout the river length. Along most of River Murray and lowland tributary sections.	• Increased flux of bed sediment. • Increased instream velocities. • Channel enlargement – width and depth.
1919-1939	• Weirs: 13 low-level, run-of-river weirs. Initially for river navigation, now maintain hydraulic head for irrigation channels. Between Albury and Darling River junction: Torrumbarry Weir (1919), Euston Weir and Lock 11, Yarrawonga Weir (1939), and Lock 10 downstream of the Darling Junction. • Trap sediment by converting hundreds of kilometres of riverine environment into a lake.	• Trapping of sediment in weir pools. • Clearwater scour downstream.
1917-Present	• Major dams and flood mitigation: Hume Weir (1936) for water supply. • Forty large (>15 m) dams on every major River Murray tributary except the Ovens River by the 1970s. The largest, Dartmouth Dam (1979) built on Mitta Mitta River. Major levee systems constructed. • Trapped sediment and altered flow regimes over the entire catchment.	• Trapping of sediment in reservoirs. • Clearwater scour downstream.

Period	Human impact	Likely impacts from Yarrawonga Weir to Picnic Point
1970-Present	• Irrigation: Increasing proportion of irrigation flows and long-duration releases below Hume Dam reversed flow seasonality. Substantial flows diverted into Upper Murray from Snowy Mountains Inter-basin transfer project. High, long duration flows increase channel erosion rates from Albury to Yarrawonga. Below there, reduced discharges are main effect.	• Reduced flood peak discharges
1950s-Present	• Water skiing: Waves from water-skiing erodes banks. Entirely concentrated in summer months coinciding with long duration irrigation flows resulting in increased bank erosion along the river, especially the Tocumwal reach.	• Sediment supply increases from bank erosion.
1970s	• Carp: Introduction of invasive carp, especially spread throughout catchment from Victoria after the 1973 flood. Direct increase in mobilising suspended sediment. • Desnagging: Major desnagging (over 20,000 logs) projects between Hume Dam and Yarrawonga Weir to increase flow conveyance (Gippel *et al.* 1992). Wood removal would have increased in-channel sediment movement mostly between Hume Dam to Yarrawonga.	• Increased flux of bed sediment. • Increased instream velocities. • Channel enlargement – width and depth. • Carp mobilising sediment.

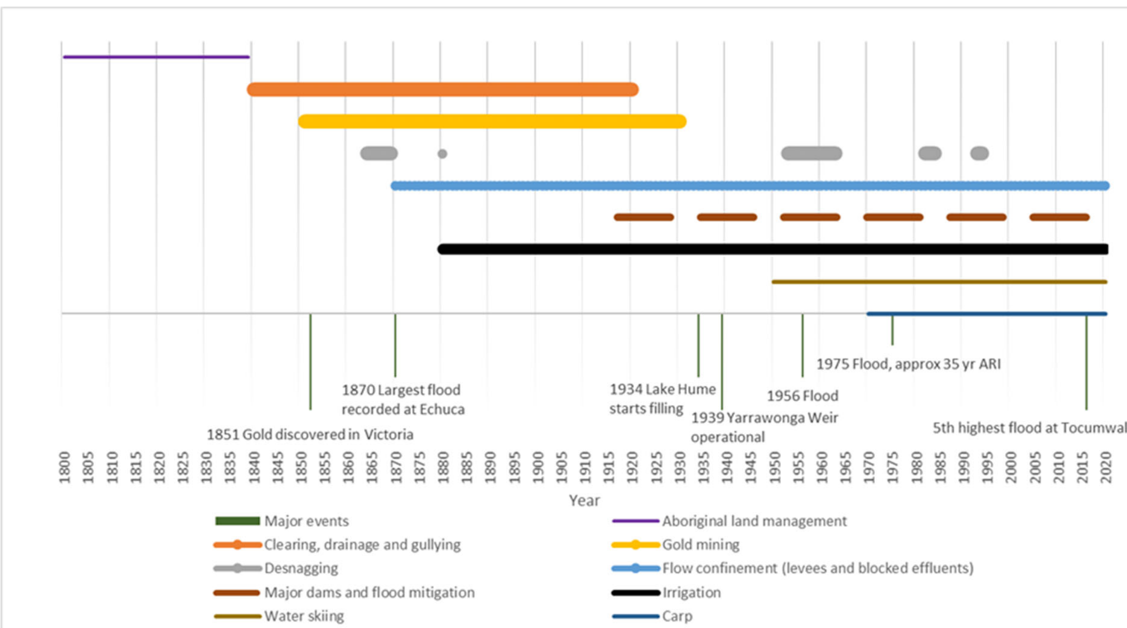

Figure 2-1. *Impacts likely to influence the sediment budget in the River Murray catchment relative to reference based on data from Rutherfurd et al. (2020). The width of the solid lines indicates the likely magnitude of change whilst the dashed lines signify the disruptions in the downstream flow of sediment.*

3 Defining the extent study of the study area

The previous work by Water Technology (2020) used a reach extent from the offtake of Bullatale Creek to Barmah (**Figure 1-3**). This reach was 100 km in length and extended over the area covered by the Barmah-Millewa Forest and by the river bathymetry, except for the most downstream 10 km. Gippel and Lucas (2002) used a reach that extended from just downstream of Yarrawonga Weir (at river chainage 1987) to Echuca (at river chainage 1706). This 281 km reach allowed comparisons with historic surveys.

There are three main sediment contributing areas that will be used in this study based on major anthropogenic changes made to the downstream continuity of bed sediment.

3.1 Downstream extent

As Picnic Point is the gauging location used to help set the regulated flows, this will be used as the position for the downstream extent of this study. This does not preclude using data available from further downstream to inform on changes upstream, there are an additional 1,681 km of the River Murray channel between Picnic Point and the coast (BOM 2020).

Table 3-1. *Catchment areas that may have supplied riverbed sediment to Picnic Point during different time periods and their maximum upstream channel distances based on the BOM Geofabric data (BOM 2020).*

Sediment supply area	Date	Catchment area (km^2)	Maximum distance upstream (km)
1: Pre-regulation	Pre - 1934	27,636	658
2: Picnic Point to Hume	1934 - 1939	12,366	352
3: Picnic Point to Yarrawonga Weir	1939 to date	1,479	169

3.2 Sediment supply area 1: pre-1934 regulation

The upstream extent of sediment supply to Picnic Point in a pre-regulation setting this would have been the whole of the upstream catchment (**Figure 3-1**). This consists of a catchment area of 27,636 km^2 and a main stem upstream length of 658 km (BOM 2020) (**Table 3-1**).

The catchment area before regulation would have been made up of the following Bureau of Meteorology (BOM) Geofabric (BOM 2020) reporting regions:

1. Part of the Murray Riverina
2. Ovens River
3. Kiewa River
4. Upper Murray River.

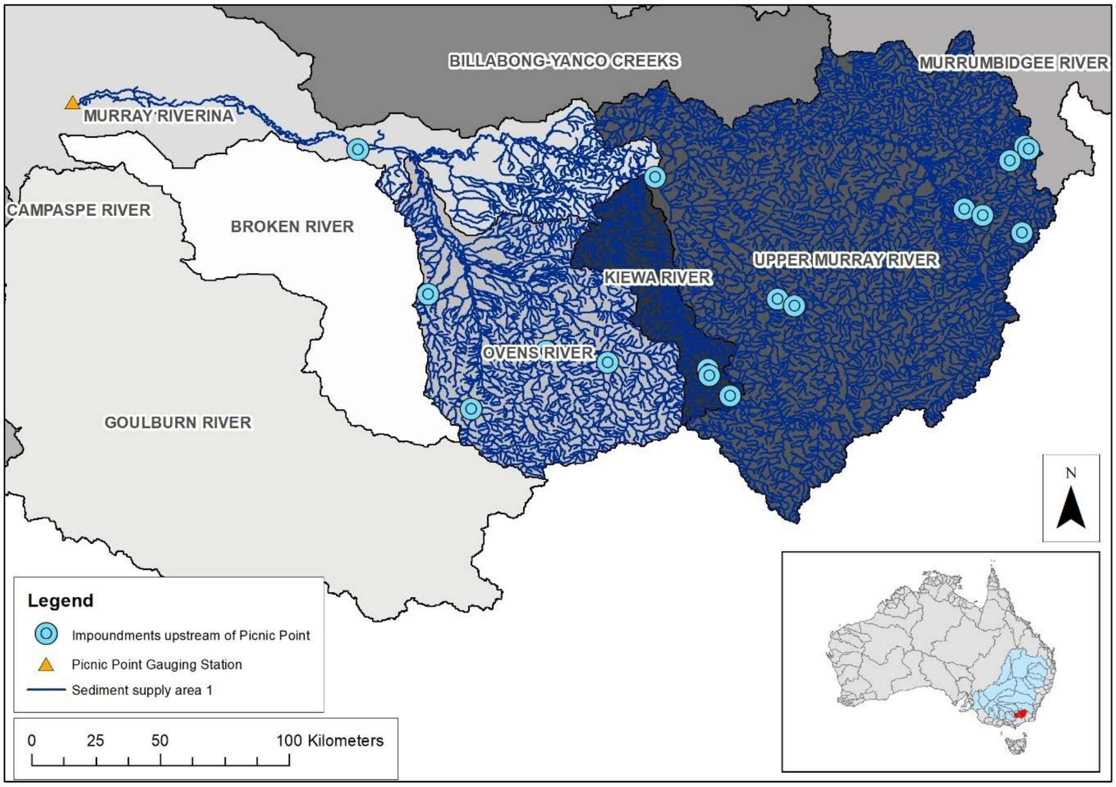

Figure 3-1. *A map of the extent of sediment supply area 1. The BOM Geofabric reporting regions are labelled in grey.*

3.3 Sediment supply area 2: post Hume regulation (1934-1939)

In November 1919 construction began on the Hume Dam (**Figure 3-2**) and the reservoir began filling in 1934. Once it began filling sediment supply downstream would be disrupted. The dam was modified a number of times and is now 42 m high and 1,615 m in length. The operating capacity is 3,005 GL with a lake size of 202 km^2.

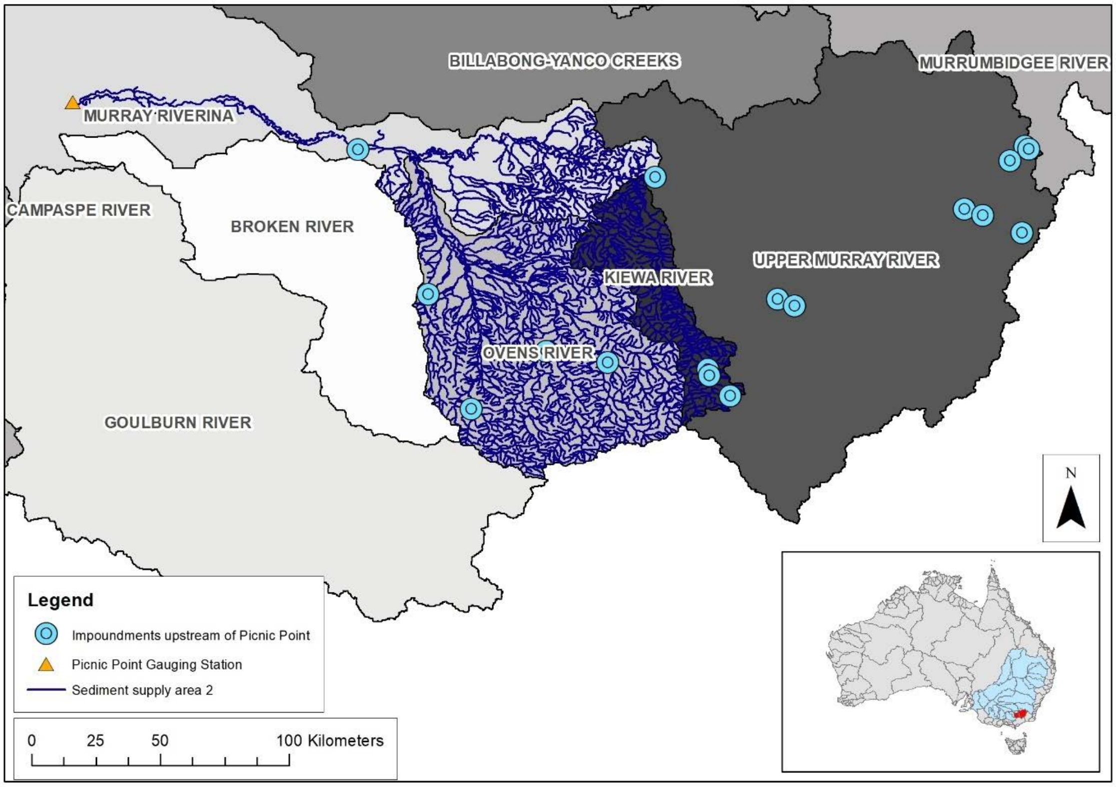

Figure 3-2. A map of the extent of sediment supply area 2.

The catchment area of the reservoir is 15,270 km² and the maximum upstream distance is 306 km (BOM 2020), this could reduce the reach that could supply bed sediment upstream of Picnic Point to 12,366 km² (**Table 3-1**). The sediment supply catchment to Lake Hume would have been reduced by the building of other subsequent reservoirs upstream, especially Dartmouth Dam that had a catchment area of 3,509 km² that was operational in 1979.

3.4 Sediment supply area 3: post Yarrawonga Weir regulation (1939 – to date)

The Yarrawonga Weir (**Figure 3-3**) began construction in 1935 and was finished in 1939. There are two groups of gates on the weir, north and south. The eight southern gates are used at all flows and the two northern gates are used during larger floods to limit scour, also termed fluvial entrainment. The capacity of Lake Mulwala is 118 GL. The main purpose of the storage is to maintain a water level 124.9 m AHD (which requires 113 GL of dead storage) to provide gravity fed irrigation channels.

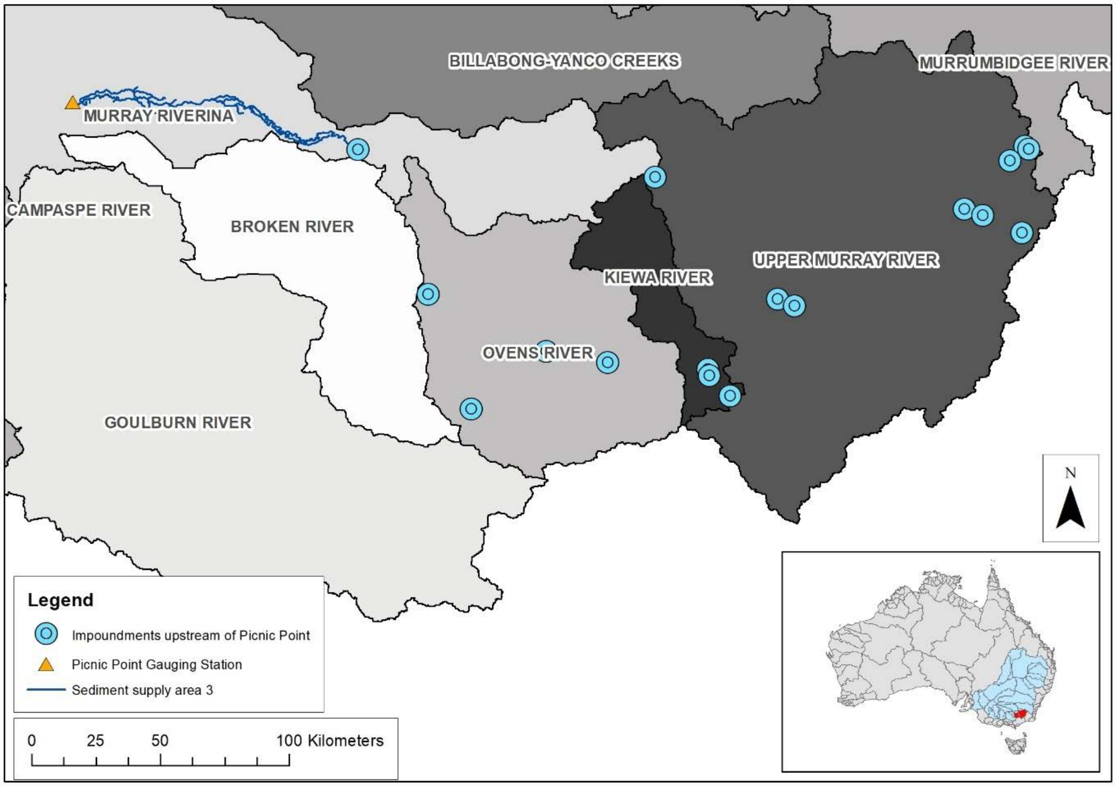

Figure 3-3. *A map of the extent of sediment supply area 3 which includes all the surrounding Murray-Riverina catchment between Yarrawonga Weir and Picnic Point.*

Yarrawonga Weir was approximately 230 km from Lake Hume and 170 km from Picnic Point with a catchment area of 26,157 km². By constructing Lake Mulwala the new catchment area for bed sediment upstream of Picnic Point was reduced to 1,479 km². The following main River Murray tributaries (shown with their catchment areas) downstream of Lake Hume would no longer have supplied bed sediment to Picnic Point:

a. Ovens River (25,655 km²)

b. Black Dog Creek (19,189 km²)

c. Kiewa River (1,729 km²)

d. Indigo Creek (197 km²)

There are only very minor tributaries that would supply sediment to the main River Murray channel in sediment supply area 3, and this is a 'losing' reach with both sediments (mainly silts and clays) and flow being carried down effluents and anabranches.

3.5 Summary

The contributing area for bedload coming into the Barmah Choke has dramatically changed with the construction and filling of Lake Hume in 1934 and Lake Mulwala in 1939. This means that sources of bed sediment can be divided into three periods that have different areas:

1. Pre-1934: the whole catchment area above Picnic Point.
2. Pre- 1939: the catchment area between Hume Dam and Picnic Point.
3. 1939 – to date: the catchment area between Yarrawonga Weir and Picnic Point.

The >20 million m^3 of coarse sand observed in the riverbed between Yarrawonga Weir and Picnic Point may have been mobilized over a combination of different time periods. Crucially, if it were considered to have been mobilized after Yarrawonga Weir was operational in 1939, then the sediment must have come from sources downstream of the weir. This area of sediment supply, therefore, will be considered in detail to understand the forms and processes that may influence the contribution of sediment and its mobility. The River Murray channel in sediment supply area 3 will be divided into two reaches based on geomorphic form and processes:

- Reach 1: Yarrawonga Weir to just upstream of Bullatale Creek (119 km).
- Reach 2: Bullatale Creek to Picnic Point (68 km).

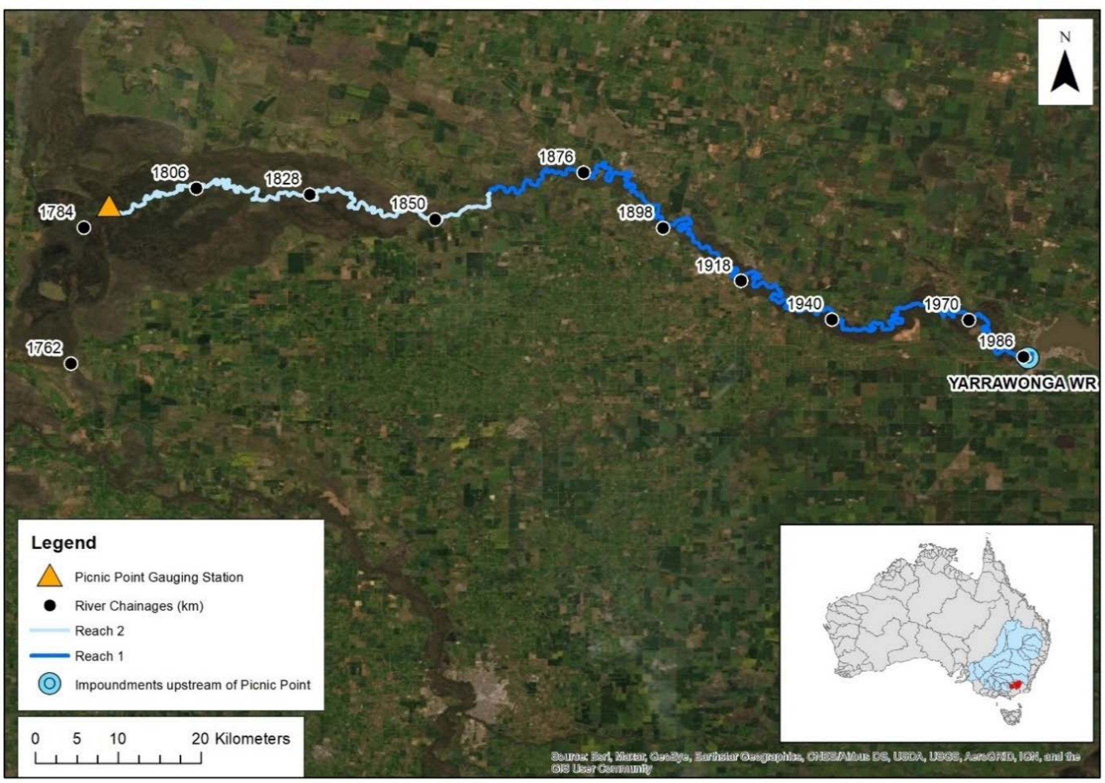

Figure 3-4. A map of Reaches 1 and 2 showing MDBA river chainages.

4 An overview of the geomorphology from Yarrawonga Weir to Picnic Point (Reaches 1 and 2)

Rutherfurd & Kenyon (2005) describe the current Barmah geomorphology that includes Reaches 1 and 2 based on the following divisions:

- **Corowa to Bullatale Creek:** The river has bankfull widths of 90 – 120 m and bankfull depths of between 5.5 – 10 m. The most prominent features of the reach are the sandy beaches on point bars.

- **Bullatale Creek to Picnic Point**: There were major offtakes into Tuppal and Bullatale Creeks at the upstream end of the reach and to the Edward River anabranch downstream. There was a decrease in sinuosity and the absence of large bends and sandy point bars. Natural levees of silty-clay of up to 1 m were on both banks. Bankfull widths varied between 50 – 160 m whilst bankfull depths varied from 3.3 – 8 m.

  The channel capacity went from 25,000 ML/d at Tocumwal down to 8,500 ML/d at Picnic Point. Flow was regulated into the Edward River system; some may also have entered Gulf Creek to the south-west and into a series of anabranching channels. The north flowing effluents join with Toupna Creek which then flows to the Edwards Rivers. The south flowing effluents join to form Tullah Creek which eventually reconnect the flow with the River Murray at the Moira Lakes.

  Lunettes and natural levees formed the constriction of the Barmah Choke. When the Goulburn and/or Campaspe Rivers were in flood they were able to reverse flow up towards Barmah.

- **Picnic Point to Bama Sandhill (~8 km downstream of Barmah township):** The channel capacity increased from 8,500 ML/d at Picnic Point to 35,000 ML/d at the Bama Sandhill. Effluent flow that left the channel upstream was able to re-enter to increase the discharge. Irregular meanders had low angles and amplitudes. Bankfull widths ranged from 38 - 210 m and depths ranged from 4 - 10 m.

- **Bama Sandhill to Goulburn River Confluence:** The Murray now passed through the bed of the former Lake Kanyapella. Sinuosity increased and bankfull widths varied from 80 – 90 m and depths from 7 -9 m. Mud drapes formed banks over silty-clays and there were sandy point bars.

This study will concentrate on the first two of these divisions and will focus on geomorphic variables that may have changed either to contribute more bedload or have altered because there was a greater bedload supply. Indicative temporal and spatial scales of adjustment in fluvial form are shown in **Figure 4-1**. These suggest that changes in reach gradient are unlikely to be observed but meander wavelength, channel dimensions and bedform configurations are likely to have had observable changes.

The description by Rutherfurd & Kenyon (2005) shows that there is a downstream progression from a wider meandering channel to one with multiple effluent channels and a smaller channel capacity. The bedload transport consequences of this downstream flow loss to effluents through the Choke will be explored.

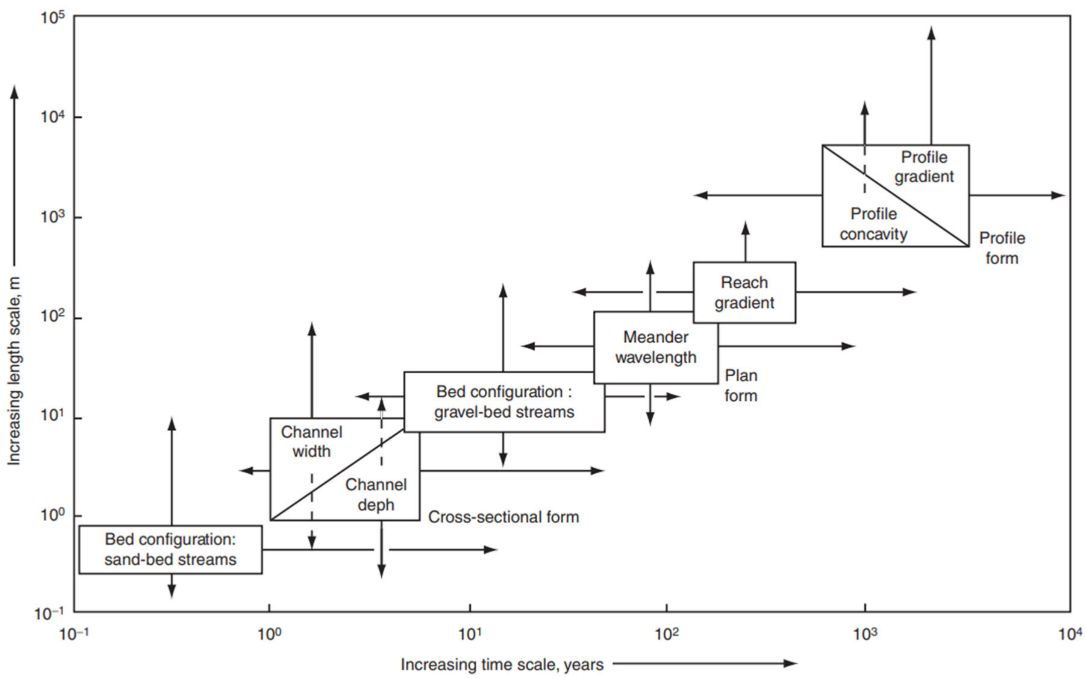

Figure 4-1. *A schematic diagram of the timescales of adjustment of various channel forms in a hypothetical basin of intermediate size (Knighton 1998).*

4.1 The geomorphology of Reach 1: Yarrawonga to Bullatale Creek

4.1.1 Planform

The floodplain of around 3 km in width upstream of the constrictions in the Barmah-Millewa Forest has meanders that, as part of their natural process of formation, erode on the outside of the bend and deposit on the inside. It would, therefore, be expected that the meanders would extend and migrate at a slow rate in the downstream direction. Disturbance in the channel may alter the rates and extent of these processes.

Channel change in this meandering and anabranching system may also occur by meander necks cutting off when the meander has become overextended and hydraulically inefficient. These cut-offs remain as billabongs on the floodplain that slowly infill with sediment deposited during flooding.

4.1.2 Boundary sediment

4.1.2.1 Size and form of bedload

Whilst there is little information on pre-disturbance riverbed grainsize and bedforms in Reach 1 there are descriptions of areas just upstream of the junction with the Ovens River. Near to what is currently Albury Hume (1931) wrote that "*the bed of the river, was in general composed of sand containing a good deal of mica*". Hamilton (1845 p.40-41) described crossing the River Murray upstream of the Ovens River in 1838, which Rutherfurd *et al.* (2020) suggested was made close to what is now Corowa. He described a meandering river that had a gravel bed, and sandy point bars. The crossing was made at a point where there was a gravel island mid-stream.

There are also limited data on the current bed sediment grainsizes. Water Technology (2021) sampled three of the point bars in Reach 1 (**Table 4-4**) (**Figure 4-2**). These point bars are a common feature on the inside of riverbeds in Reach 1. As part of this study the bare sand area of 122 point bars in the reach was calculated as approximately 1,100,000 m^2 (**Appendix A3**). The surface sediment of the point bars was made of >96% sand in all the samples with the majority of this sand being coarse, the rest of the samples were comprised of gravel.

Table 4-1. *Point bar sediment sample sizes on the River Murray (Water Technology 2021)*

Sample	**Total gravel >2 mm (%)**	**Coarse sand 0.2 – 2 mm (%)**	**Fine sand 0.02 – 0.2 mm (%)**	**Silt 20 – 200 µm (%)**	**Clay < 2 µm (%)**
Beach KP2	2.5	96.2	1.3	0.0	0.0
Beach KP3	2.7	96.1	0.6	0.0	0.0
Beach T1	4.1	93.9	2.0	0.0	0.0

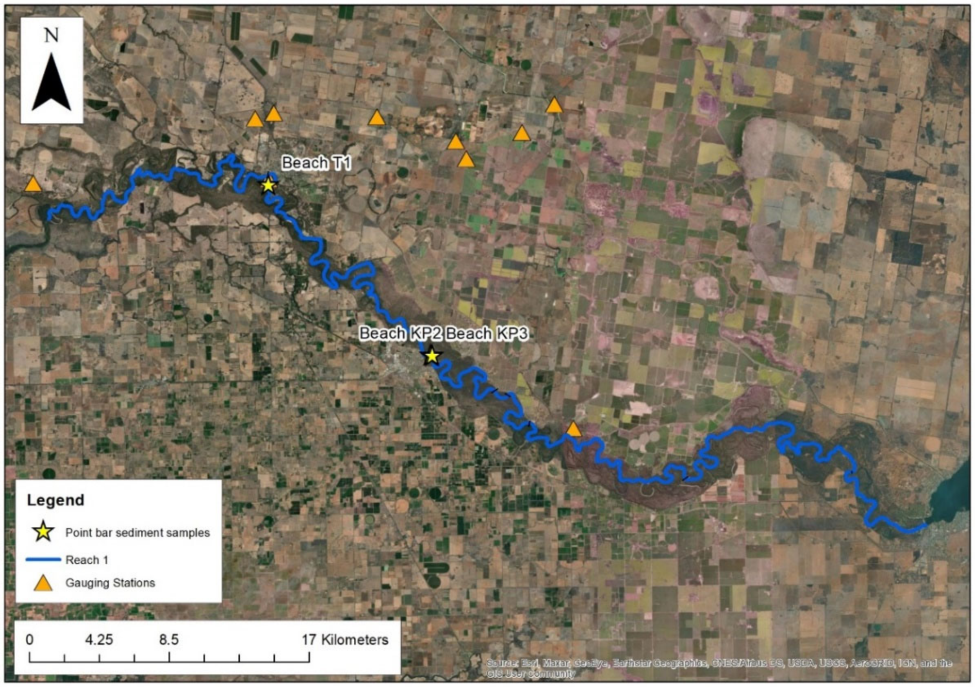

Figure 4-2. A map of Reach 1 showing the position of point bar (also termed beach) sediment samples taken by Water Technology (2021).

In the current channel the average depth of bed sediment in Reach 1, based on the SA (2021) data (**Figure 1-11**), was 1.23 m (**Appendix A1.4**). Splitting the reach into 10 km sections showed that the average depth of sediment was relatively consistent, varying between 1.06 – 1.33 m. A similar trend of relative consistent sediment volumes is shown in **Figure 4-3**. The reach has approximately 16 million m^3 of bed sediment (**Appendix A1.4**).

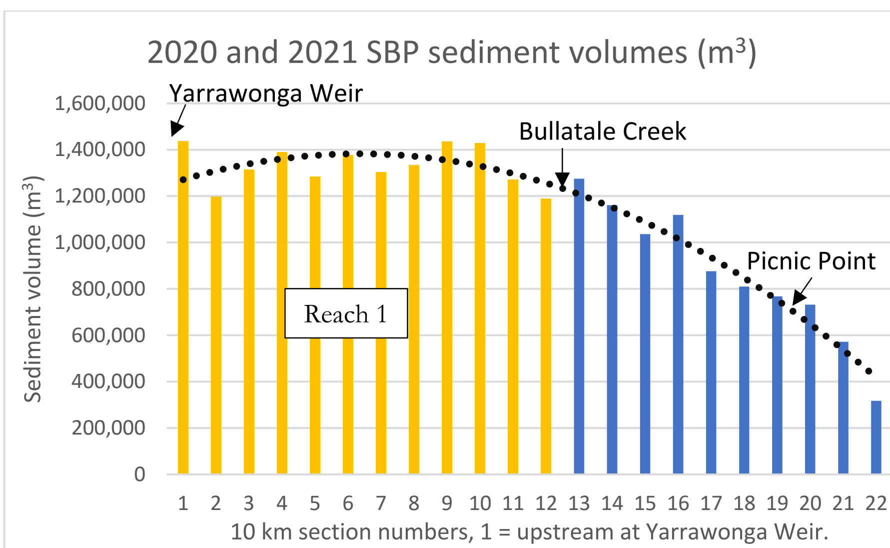

Figure 4-3. The volume of sediment calculated in 10 km sections of the riverbed. Section 1 starts at Yarrawonga Weir and Section 22 ends at Barmah township. Reach 1 (Sections 1-12) has been coloured yellow. A 2nd order polynomial trendline is shown in black.

Gippel and Lucas (2002) observed that downstream of Yarrawonga Weir a resistant armoured layer had developed, which they observed on point bars. They suggest that this layer was comprised of ancestral channel gravels supplied from erosion of lenses of the sediment in the riverbank. The SBP depth and acoustic profile (**Figure 4-4**) (SA 2021a) shows a relatively planar bed surface without the dunes observed downstream. The sediment depths of 1-3 m also suggest that the armour layer protects coarse sand beneath it from erosion. It is not known exactly how far downstream this armoured layer extends, however, the shallower SBP depths around 2 km downstream of the weir could be an area of bed scour as a result of more limited armouring.

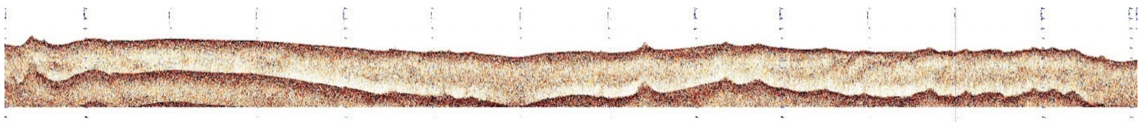

Figure 4-4. A section of the 2021 SBP data downstream of Yarrawonga Weir showing a relatively flat bed surface overlying 1-3 m of sediment. Upstream is the right of the image.

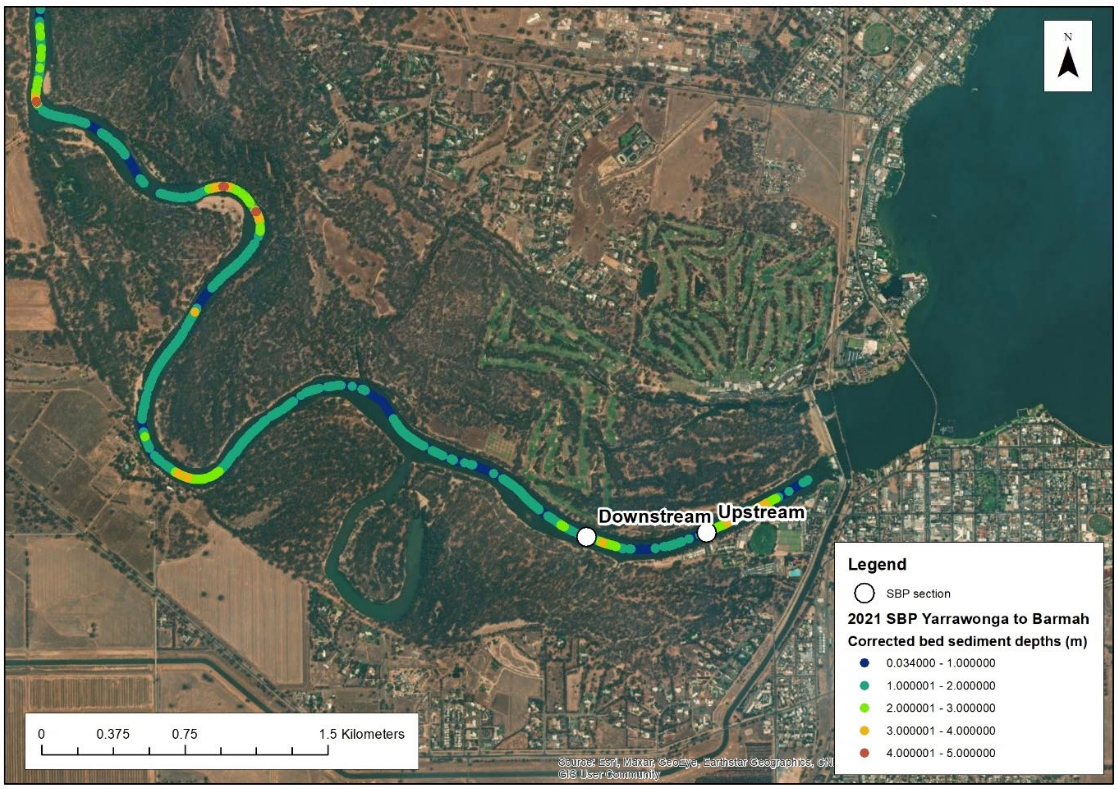

*Figure 4-5. A map showing the up and downstream extent of the data included in **Figure 4-4** relative to Yarrawonga Weir, show on the top right of the map. Depths of the 2021 SBP survey are plotted.*

4.1.2.2 Riverbank sediment

The banks of the channel consist of a combination of laterally accreted sandy material and the vertically accreted silts and clays that are deposited during overbank flooding. Bren *et al.* (1988) suggested surrounding soils in this reach are made of a swelling brown clay composed substantially of illite or kaolinite overlying sand lenses. Gippel and Lucas (2002) described the banks from Yarrawonga to Echuca as being resistant because of their 55-75 % content of silts and clays. This would mean that the banks were comprised of around 25-45 % sand or coarser grainsizes. There is relatively poor information on the particle sizes and their layering in the riverbanks of the Murray from Yarrawonga to Bullatale Creek. Hence it is difficult to ascribe an accurate coarse sand supply that may come from bank erosion in this reach.

4.1.3 Geomorphic changes observed in Reach 1

4.1.3.1 Changes in sinuosity

The sinuosity of the of the channel (calculated as the *Length of the channel/Valley length of the channel*) shows whether there has been a major straightening or increase in channel length. This provides an initial indication of sediment production from riverbank erosion. Since the 1860s there have been 22 meander cut-offs on the River Murray between the Hume Dam and the Darling Junction causing only a small net shortening of the river's path length by 4.7 %. (Rutherfurd *pers comm.* 2020).

4.1.3.2 Changes in bankfull width

Rutherfurd and Kenyon (2005) discuss some of the changes to the channel that have occurred since European settlement. The channel from Yarrawonga downstream has widened based on comparisons with the 1876 survey (**Figure 4-6**). The survey data suggests that bankfull widths have widened on average by 30-40 m (47 % of 1876 width) since 1876 upstream of Bullatale Creek.

These data have been re-examined and compared against LiDAR data from 2015 (**Appendix A2)**. The width changes between 2002 and 2015 produced large amounts of channel contraction that was not evident in the images. The 2002 data was collected by Gippel and Lucas (2002) with a laser range finder appear to have overestimated the bankfull width, especially between Yarrawonga and Bullatale Creek. These data have been excluded from analysis.

Comparisons of the bankfull widths from Yarrawonga Weir to Bullatale Creek gave average differences of +33 m from 1876 to 1981, and -8 m from 1981 to 2015. These data can be converted to rates of channel widening of +0.3 m/yr followed by contraction of -0.08 m/yr.

Based on data from Rutherfurd (1992) and Gippel and Lucas (2002), Rutherfurd and Kenyon (2005) suggest that widening may have resulted from benches being cut into the banks at the level of the regulated flow. Gippel and Lucas (2002) observed that the levels of the benches were not constant compared to the water level. They suggested that the different bench elevations may be the result of changing levels of regulation after the construction of Hume Weir and Dartmouth Dam. These benches may be up to 20 m in width. The benches and widening are thought to have been caused by long duration flows through the irrigation season, boat wash, and degradation of extensive reed (Phragmites) beds.

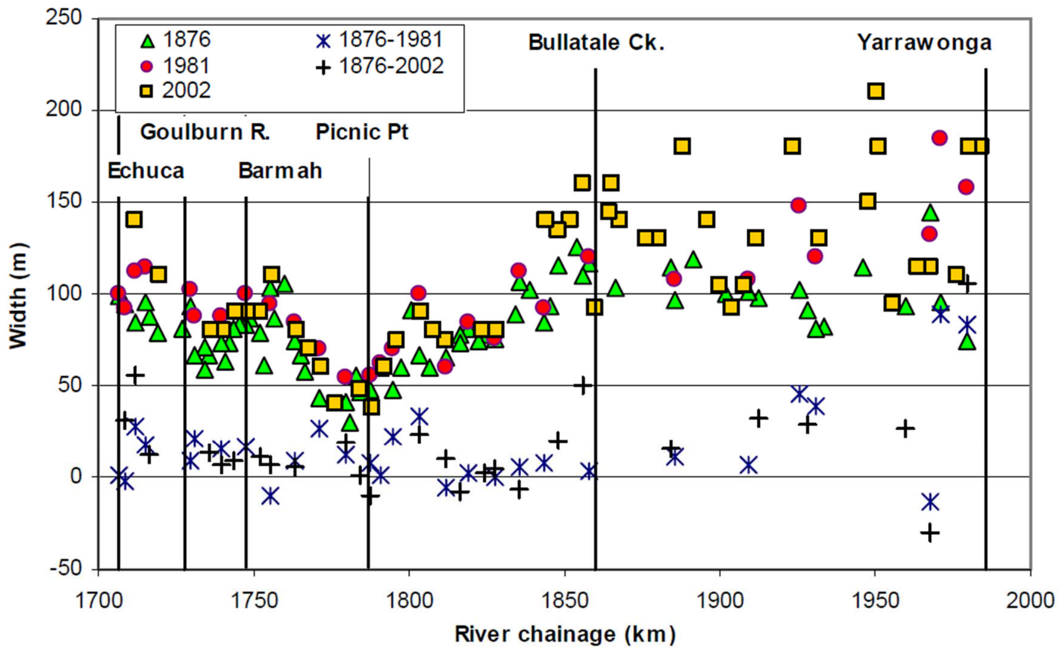

Figure 4-6. *Historical channel changes observed on the River Murray between Yarrawonga and Echuca. Crosses represent the change in metres between the 1876 survey width and the 1981 or 2002 survey, whilst the other shapes represent the surveyed widths (Gippel & Lucas 2002).*

4.1.3.3 Changes in bankfull depth

Whilst there was limited data on channel depths the SPB data (SA 2021a) showed that pools on the outside of meander bends had sediment depths of over 4 m. This accumulation of sediment was higher than expected, nearly completely filling many of the pools. Average sediment depths in 10 km sections were relatively consistent all the way through the reach (**Figure 4-3**). This would suggest that the bankfull depth has decreased all the way from Yarrawonga Weir to Bullatale Creek and that greatest decreases have been in pools on meander bends.

4.1.3.4 Changes in point bar area

As part of the study, georectification of 1940-1950s aerial photography had been undertaken. The rectification was not good enough to establish channel movement based on relative channel positions and so it was not used to determine the change in area bars based on their difference in spatial location. Instead, the unvegetated areas of sand bars in the imagery was undertaken and then in the current imagery from ESRI (2019) at a scale of 1:2,500. The area of bare sand without continuous vegetation has been digitised as consistently as possible (**Appendix A3**). Examples of the imagery are shown in **Figure 4-7** and **Figure 4-8**.

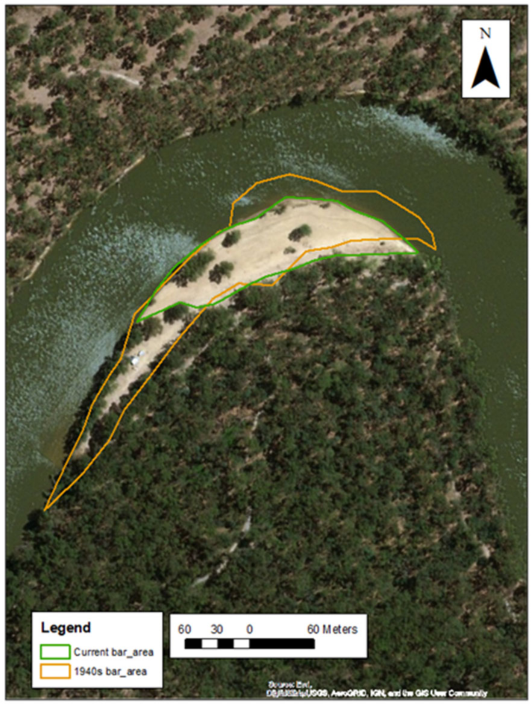

Figure 4-7. *Recent (2019) aerial imagery shown with the extent of the bar digitised from the current and 1940s imagery based on the extent of sand without continuous vegetation.*

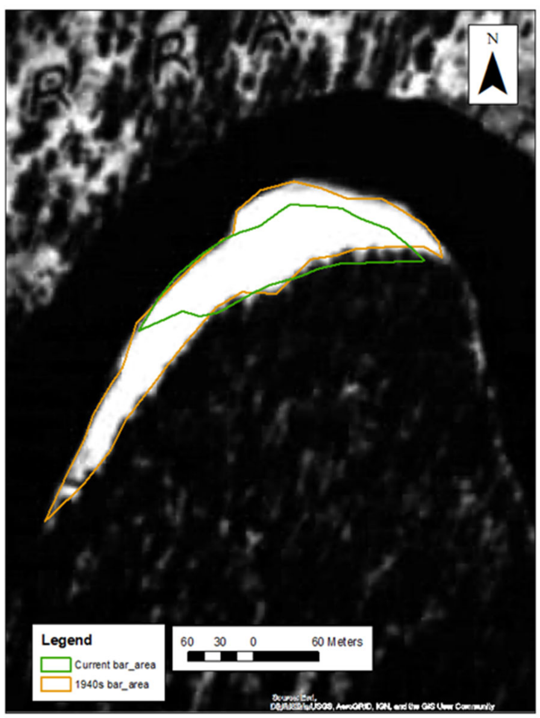

Figure 4-8. *1940s aerial imagery shown with the extent of the bar digitised from the current (2019) and 1940s imagery based on the extent of sand without continuous vegetation.*

There will be errors from different water levels and the projection of images as well as the determination of 'mobile sand' unvegetated areas. However, the gross areas help clarify how these features have changed over time. The reduction in unvegetated area was estimated to be 400,000 m^2, or 27% of the 1940s – 50s extent. However, this reduction in area strongly appeared to be as a result of vegetation establishment of the bars rather than the erosion of the bars. It is difficult to be precise about this but in many examples the relative position of the bar appears to be similar, but the amount of vegetation has increased. This could be the result of a number of factors such as more recent better stock exclusion, changes in flows regimes resulting in different sediment mobility and transports rates, different climatic conditions, or other land management decisions.

The reduction in active bar area does not appear to be as the result of erosion of the bars. However, there is the possibility that stabilisation of the bars by vegetation and regulated flow levels may result in the margin of bars being eroded. Without stabilisation the whole bar surface would be mobile when inundated with sediment being deposited and eroded. Stabilising the sand and maintain flow levels may produce an eroded scarp upstream. LiDAR data does not appear to support the fact that this erosion is extensive.

Table 4-2. Summary Box 2

- Reach 1 is a meandering channel set within a narrow floodplain. It has not significantly changed in channel length, and therefore, sinuosity since the 1860's.
- The bankfull widths of 90 – 120 m are the result of widened 1876 to 1981. On average the channel has widened by 33 m, however, from 1981 to 2015 there was a slight average contraction in bankfull width of 8 m.
- There is relatively little information on pre-disturbance and sediment on the bed and banks. The point bars sampled were mainly comprised of coarse sand.
- Point bars appear to have reduced in their area of unvegetated coarse sand by 27% from the 1940s to 2019. The reduction is not thought to be from erosion but from the encroachment of vegetation.
- The SBP data shows an average depth of sediment was 1.23 m in the reach which equates to a volume of 16 million m^3.
- Pools have nearly completely infilled resulting in bed sediment thicknesses of over 4 m.

4.2 The geomorphology of Reach 2: Bullatale Creek to Picnic Point

4.2.1 Planform

There is a transition from a single channel system set in a narrow floodplain with sandy point bars into a multichannel system sitting on a low angled alluvial fan. The apex of the fan is upstream and it spreads out downstream to the Cadell Fault. Gower *et al.* (2020) describe this type of river as a distributary fluvial system (DFS) based on work by Weissman *et al.* (2010). These systems are distinguished in planform by the following characteristics (Hartley *et al.* 2010):

- a clear apex from which channel systems (both active and abandoned) diverge downstream,
- the presence of a distinguishable positive topographic feature centred on the apex, with slopes decreasing away from the apex both laterally and downstream,
- the river associated with the DFS commonly displays distributive characteristics, often bifurcating into smaller channels,
- no tributaries join the DFS below the apex,
- evidence for abandoned channels with a divergent or arcuate pattern away from the apex, and
- radial or downstream length > 30 km.

Hartley *et al.* (2010) classify six different categories of DFSs of which the Barmah-Millewa Forest would be a 'single sinuous channel that bifurcates (divides) downstream into smaller sinuous channels'. Gower *et al.* (2020) suggest that this type of DFS is a 'Single-Thread, sinuous anabranching system' based on the three refined categories of DFSs described by Davidson *et al.* (2013). It would be expected that as the river channel moves downstream with no tributary inputs, and flow is lost to effluents, that the main channel would reduce in discharge. This is contrary to most single channel fluvial systems where the catchment area increases down-valley, along with the discharge. When the channel loses discharge it would be expected that its dimensions of width and depth would also decrease.

As the channel fills with sediment, it also builds levees on the floodplain. The whole system can become perched above the surrounding floodplain (**Figure 4-9**). This can result in a flood, or series of floods, causing the channel to break out and form a new channel on the floodplain (avulse) or reoccupy a palaeochannel.

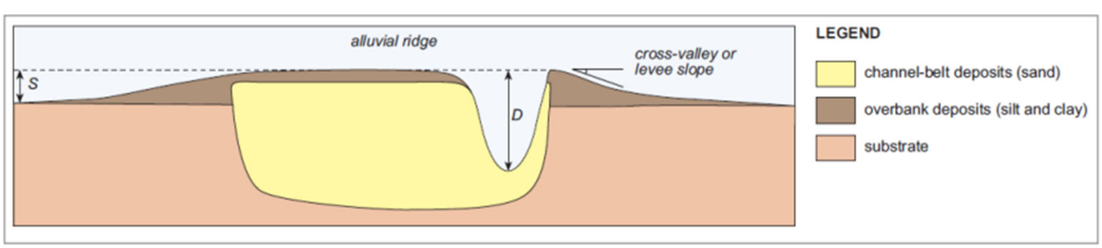

Figure 4-9. *A conceptual model showing the cross-section of an anabranching channel that is close to avulsion (Baky 2018)*

4.2.2 Effluent channels

The distributary or effluent channels in the Barmah-Millewa Forest form in different ways. In the reach from Yarrawonga to Echuca, Baky (2018) describes the evolution of channels on the floodplain. Channels develop on the backslope of levees (floodplain side), these levee channels can incise down cutting through the levee and connecting with the main channel (**Figure 4-10**). The levee channels can slope towards the channel (entrant) or away from it (effluent). They can also cut back into the floodplain and develop their own levees. The result is that the levee channel beds can be at varying elevations in the riverbank of the trunk stream. They occur on the outside of meander bends where there is a prominent levee. They have the potential to coalesce over time and form an anabranch.

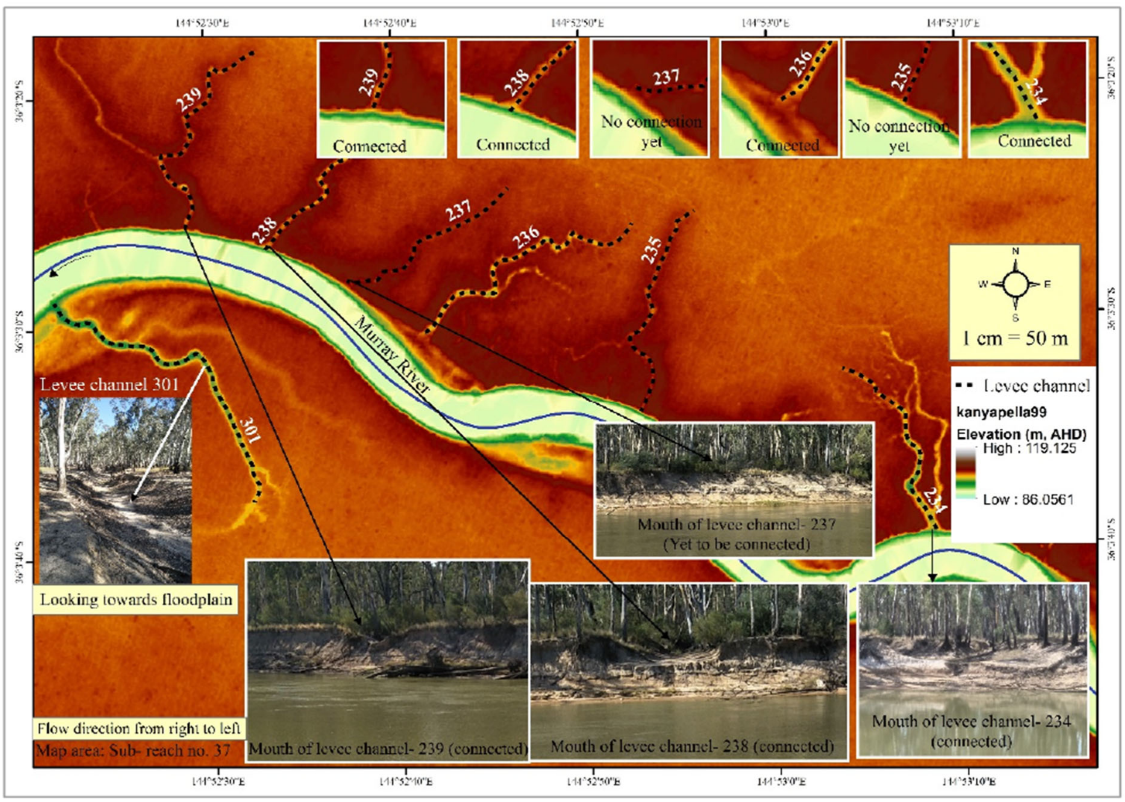

Figure 4-10. *Map showing the levee channels (dotted line) along the River Murray. Some of the levee channels shown are yet to be connected with the main channel, whereas others are already connected (see inset maps and photographs) (Baky 2018 p. 4-30)*

There is no clear pre-European reference condition for the elevations of effluents in the Barmah-Millewa Forest that allows an understanding of whether they were able to transport any bed sediment from the River Murray. To be able to transport the sand sized sediment they need to be very close to the elevation of the bed of the River Murray.

The Adelaide Observer (1857 p.7) reported that *"Tuppal's Creek, the first of the series of anabranches which diverge from the main stream to form the Edward River, does not abstract water from the Murray except during the freshets. The Gulpha Creek, or chief feeder of the Edward River, was abstracting from the Murray on March 31st (1857) a small quantity of water; its width near point of departure from the Murray was 110 feet, and greatest depth 12 ½ feet. Whenever the Murray is a little lower than it was found to be when the Gulpha Creek was examined, no water would be conveyed away by the latter, but in times of flood the Gulpha affords an outlet for an immense volume of the surcharged waters of the Murray."*

It would be expected that at the end of March natural flows on the River Murray would be near to baseflow and so Gulpa Creek (then referred to as Gulpha Creek) would not be far above the bed level of the Murray if it were taking flows.

Strom and Ferguson (1940) examined breakaways (effluents) in the Barmah-Millewa Forest on the 17th and 18th of April 1940 to assess their influence on regulated flows (**Figure 4-11**). There was a range of elevations over which they were connected. These were reported based on the gauge height at Albury during the field visit. Upstream effluents were regulated, however, Gulf Creek used to be connected at well below the 1940 summer regulated flow. The downstream effluents below Picnic Point were all connected during the 1940 summer regulated flow.

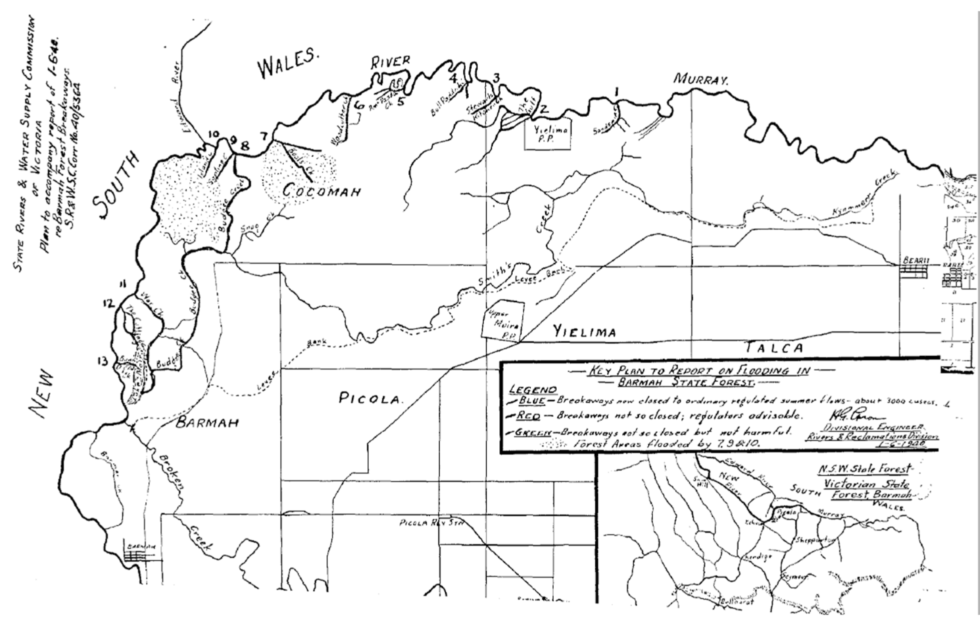

Figure 4-11. A map showing the numbered locations of breakaways (effluents) that were examined in 1940 to assess their connection with the main channel. A colour figure was not available. (Strom & Ferguson 1940 p. 8)

An article from 1953 (The Riverine Herald 1953) discusses how one creek (effluent) had been deepened to allow water to be diverted to the Bullatale Trust and that the regulator had been destroyed in a flood. This resulted in the flooding of 50,000 acres of forest. It should, therefore, not be assumed that effluents have remained at their pre-European elevations.

As well as effluents there are floodplain channels in the Barmah-Millewa Forest that include rills and pinnate drainage systems. The small channel networks were also proposed by Baky (2018) to be components of anabranch formation in these types of systems. These observations indicate how this type of river system should, in an undisturbed state, be regularly connected to its floodplain both in terms of water and the sediment suspended carried by it.

Table 4-3. *Details of effluents in 1940 that appear in* ***Figure 4-11*** *adapted from (Strom & Ferguson 1940). The rating table for Albury from 28/07/1937-05/03/1941 has been used to convert reported stages at Albury to discharges. A discharge of 72.6 m^3s^{-1} at Albury is suggested to be equivalent to the ordinary regulated summer flow level in 1940.*

Effluent number	Effluent name	Width (m)	Depth (m)	Connected discharge based on discharges at Albury	Modifications	Comments
1	Sandspit Creek	1.5	6	0.9 above 72.6 m^3s^{-1}	Controlled flows: temporary embankment	
2	The Gulf				Controlled flows: regulators	Used to be connected at 45 m^3s^{-1} at Albury. Rapid erosion was occurring
3	Stewarts Kitchen Creek	3	0.5	206 m^3s^{-1}	Controlled flows.	
4	Bull Paddock Creeks	3	0.9	206 m^3s^{-1}	Controlled flows.	
5	Punt Paddock Lagoon	12	2.4	140 m^3s^{-1} approx.	Controlled flows.	Temporary blocked
6	Woodcutter Creek Lagoon				Controlled flows.	Temporary blocked
7	Boals Creek	8	2.1	87 m^3s^{-1} approx. ordinary regulated summer flow level		Partly blocked by willows. Allows frequent flooding to 5.7 km^2 acres of forest
8	Budgee Creek	6	1.8	117 m^3s^{-1} approx. ordinary regulated summer flow level		Passes along a natural and well-defined watercourse which empties into the Moira or Barmah Lakes
9	Sapling Creek	8	2.7	72.6 m^3s^{-1} approx. ordinary regulated summer flow level		Floods 10 km^2 over 72.6 m^3s^{-1} at Albury
10	Island Creek	11	1.5			
11	War Creek	11	3	Flow depth of 0.6 m (0.14 m^3s^{-1}) at 72.6 m^3s^{-1}		Flows into Moira Lake
12	The Cutting	15	4	Flow depth of 1.5 m (10 m^3s^{-1}) at 72.6 m^3s^{-1}		Flows into Moira Lake
13	Bunny Digger Creek	9	3.4	Flow at depth of 0.9 m (0.42 m^3s^{-1}) at 72.6 m^3s^{-1}		Flows into Moira Lake

4.2.3 Boundary sediment

4.2.3.1 Size and form of bedload

Gower *et al.* (2020) described the system as one that has decreasing transport capacity downstream because of the effluents. They observed relatively deeper bed sediment at similar positions to effluent offtakes, indicating that deposition was relatively rapid once the flow was reduced (**Figure 4-12**). The dominant main channel fills with sediment from upstream to downstream as the transport capacity declines as it loses flow to effluents, but little sand sized sediment is transported out of the channel. Eventually the amount of sediment in the channel results in an avulsion, creating a new main channel.

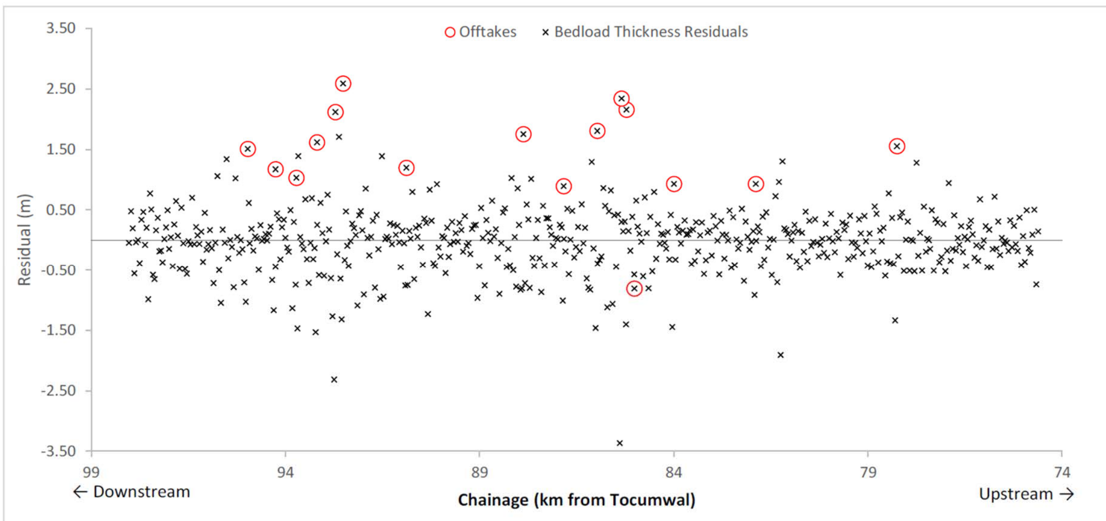

***Figure 4-12**. De-trended bedload thickness residuals based on 2020 SBP data (SA 2020) plotted against the location of offtakes (Gower et al. 2020).*

The SBP data (SA 2020; 2021a) analysed in 10 km reaches gives an average depth of 1.25 m, slightly deeper than the 1.23 m found in Reach 1 (**Appendix A1.4**). There is a gradual increase in average depths from 1.16 m in section 13 up to 1.51 m in section 19.

The volume of sediment in the bed of the channel in Reach 2 was around 7 million m^3. The decreasing channel dimensions downstream mean that even though there were increases in average sediment depths the sediment volumes on the bed declined (**Figure 4-13**).

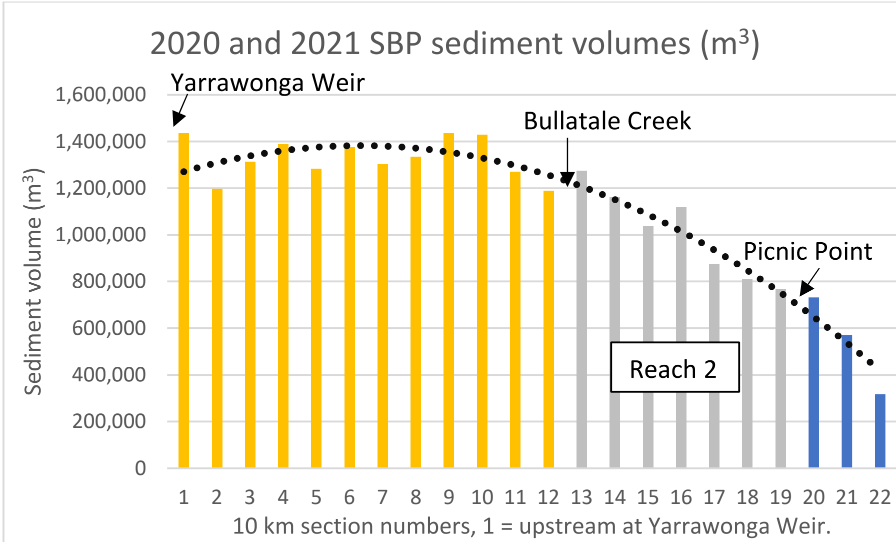

***Figure 4-13**. The volume of sediment calculated in 10 km sections of the riverbed. Section 1 starts at Yarrawonga Weir and Section 22 ends at Barmah township. Reach 2 (Sections 13-19) has been coloured grey. A 2nd order polynomial trendline is shown in black.*

There was limited data available on the pre-European settlement character of bed sediment in the River Murray in this reach. Sampling by Water Technology (2021) found clay dominated sediment underlying the current bed coarse sand, which indicates that this was an earlier bed surface over which mobile bedloads have accumulated. Desnagging reportedly released sand that had accumulated around pieces of large wood. There were also bars of sand where desnagged wood was taken to be burnt. We do not know if this sand was mainly fine or if it was coarse like the current bedload. However, it would be expected that as the transport capacity declines in the downstream direction there would be an associated decrease in grain size. Hence, if a mix of coarse and fine sands were mobilized upstream of Bullatale Creek we would anticipate mainly finer sands further down the channel at Picnic Point.

Pietsch & Nanson (2011) describe a similar DFS on the Gwydir River, NSW using historic pre-disturbance survey information. The Gwydir River is the main trunk stream. Flow in the trunk stream is governed by the elevation of the effluent channels above the bed (**Figure 4-14**). The effluents of the Mehi River and Carole Creek are high up on the riverbank, elevated above the bed. The Mehi River had the lowest level off-take from the trunk stream, but this had been artificially incised by 2.3 m between 1902 and 1936. Pietsch & Nanson (2011) suggest that this may have slightly increased the bedload carried by the Mehi River and other incised effluents.

The trunk stream carries most of the bedload whilst the effluents receive and transport very little. The bedload in the Gwydir River was gravels and sands between sections of channel that had silt/clay beds. The coarser bedload deposits were usually thin, around 0.3 m. Upstream the bed form was a plane bed with limited roughness whilst downstream the bed had dune forms. The dune forms were suggested to increase the channel roughness. The size and distribution of sediment in the Gwydir River appear similar to the River Murray, with the exception that there may have been greater loads of large wood in the River Murray enabling more sand to be trapped.

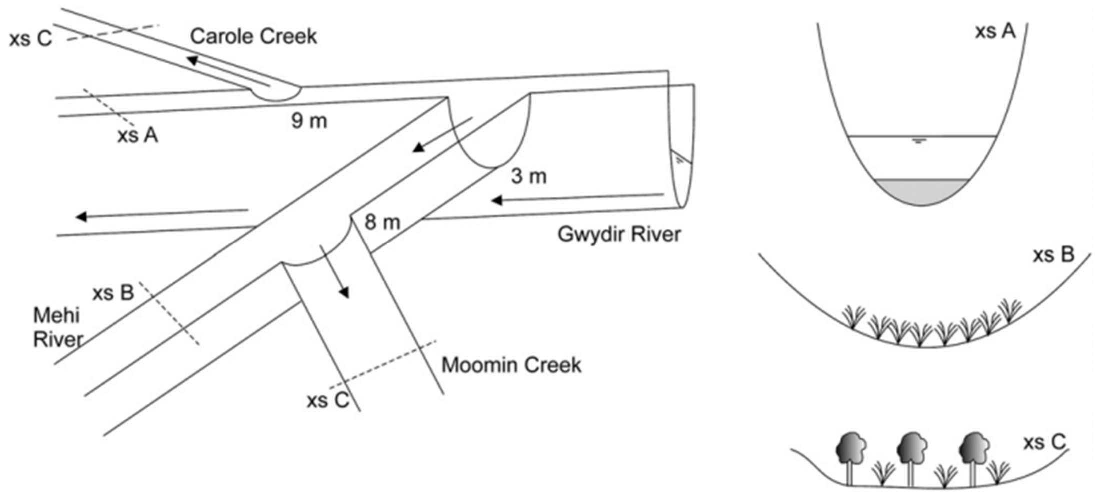

Figure 4-14. Schematic of channel off-take architecture and its influence on bedload transport and in-channel vegetation. Values beside each off-take are (pre-development) heights above bed of trunk channel. Cross-section (A) shows possibility of bedload (shaded grey in cross section A) transport in the Gwydir River at flows below the level necessary to allow distributary flow. It also highlights the deep, narrow channels free of in-channel vegetation. Sections (B) and (C) show the wider vegetated effluents that only intermittently have flows (Pietsch & Nanson 2011 p. 161)

Water Technology (2020; 2021) sampled the current surface bed sediment at the locations show in **Figure 4-15**. The sediment was mainly >90 % coarse sand (0.2-2 mm in diameter) (**Table 4-4**). There may be a downstream change in sediment size with fine sand dominating more frequently after Picnic Point.

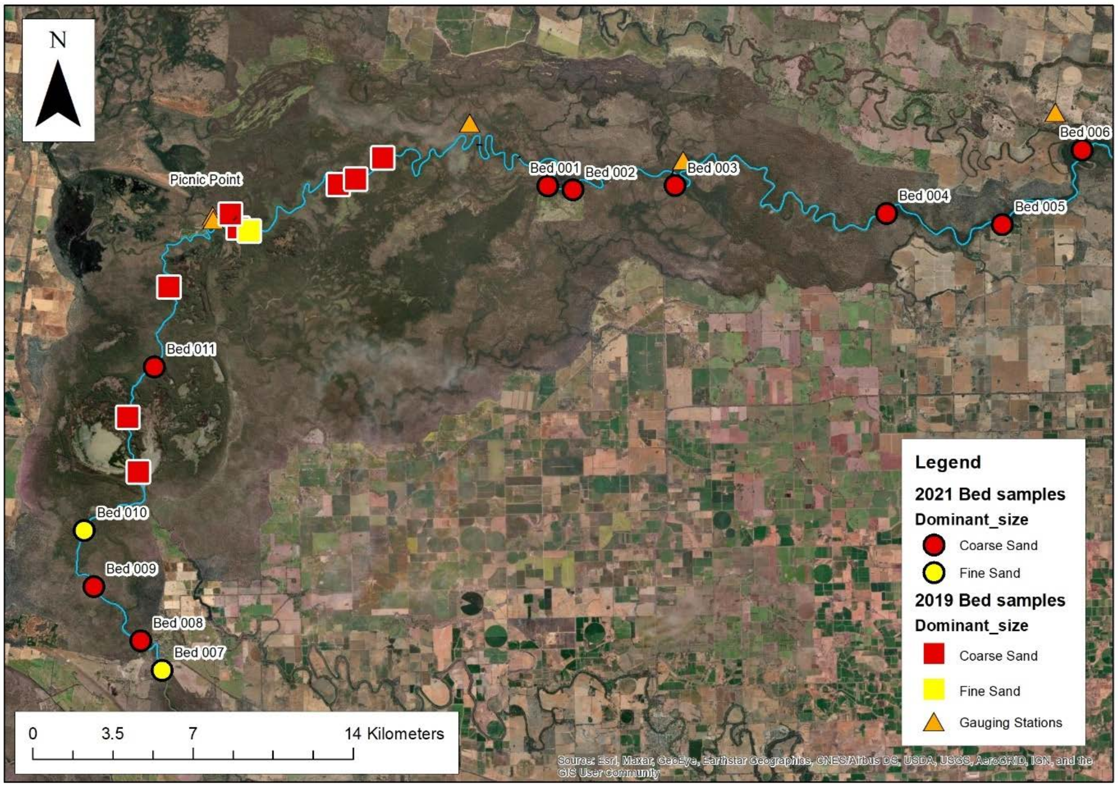

Figure 4-15. Sediment sampling locations on the River Murray through the Barmah Forest (Water Technology 2020; 2021)

Table 4-4. Bed sediment sample sizes on the River Murray (Water Technology 2021). Sample 109, which was a separate silt and clay unit at the base of sample 009 has not been included as if was not representative of the mobile bed sediment.

Sample	Moisture Content (%)	Total gravel >2 mm (%)	Coarse sand 0.2 – 2 mm (%)	Fine sand 0.02 – 0.2 mm (%)	Silt 20 – 200 µm (%)	Clay < 2 µm (%)
Bed 001	22.0	0.0	98.3	1.7	0.0	0.0
Bed 002	19.2	0.8	95.2	4.0	0.0	0.0
Bed 003	20.2	1.2	95.1	3.7	0.0	0.0
Bed 004	16.6	2.5	92.7	4.7	0.0	0.0
Bed 005	20.0	2.4	93.8	3.8	0.0	0.0
Bed 006	15.6	6.7	84.7	7.9	0.7	0.0
Bed 007	20.6	6.9	13.2	49.4	7.2	23.3
Bed 008	20.3	1.9	92.7	4.8	0.6	0.0
Bed 009	18.8	1.1	84.7	6.6	1.9	5.7
Bed 010	21.8	0.5	3.8	71.6	13.0	11.2
Bed 011	21.1	0.6	95.0	2.8	1.6	0.0

The sandy bedload in the River Murray would be transported in dune structures if the sediment were not supply limited. The SBP recorded dunes with a crest-to-crest length of 30-50 m in both the most upstream and downstream extents of their 2020 survey (**Figure 1-7**) (SA Water 2020). These dunes were more pronounced in straighter river sections and had heights of between 0.5- 1 m (**Figure 4-16**). If dunes were present in the pre-European settlement channel the bed waves would probably be slower moving and lower in amplitude with large wood causing a more diverse bed topography.

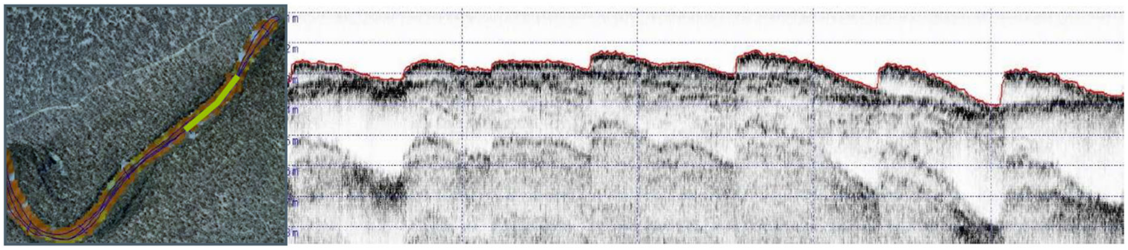

Figure 4-16. Dune structures with a crest height of around 1 m observed in the River Murray using a sub bottom profiler over a 300 m length of bed shown by the yellow line in the map image. Flow is from right to left in the images (SA 2020).

As the channel enters the Barmah-Millewa Forest more flow would have been lost to effluents in the natural system. These are now regulated with structures so that they mainly take flows during seasonal and unseasonal flood events. The loss of flow and lower channel capacity would have created a depositional zone with bed sediment being deposited in the main channel. Downstream of Picnic Point to The Narrows the channel slope increases from 0.00009 m/m to 0.0002 m/m (**Figure 4-17**). Increasing the slope in this section raises the transport capacity and sediment would be expected to be more efficiently moved through this section. Hence, we would expect a depositional zone, a transportation zone and then as the channel rewidens towards Barmah another depositional zone.

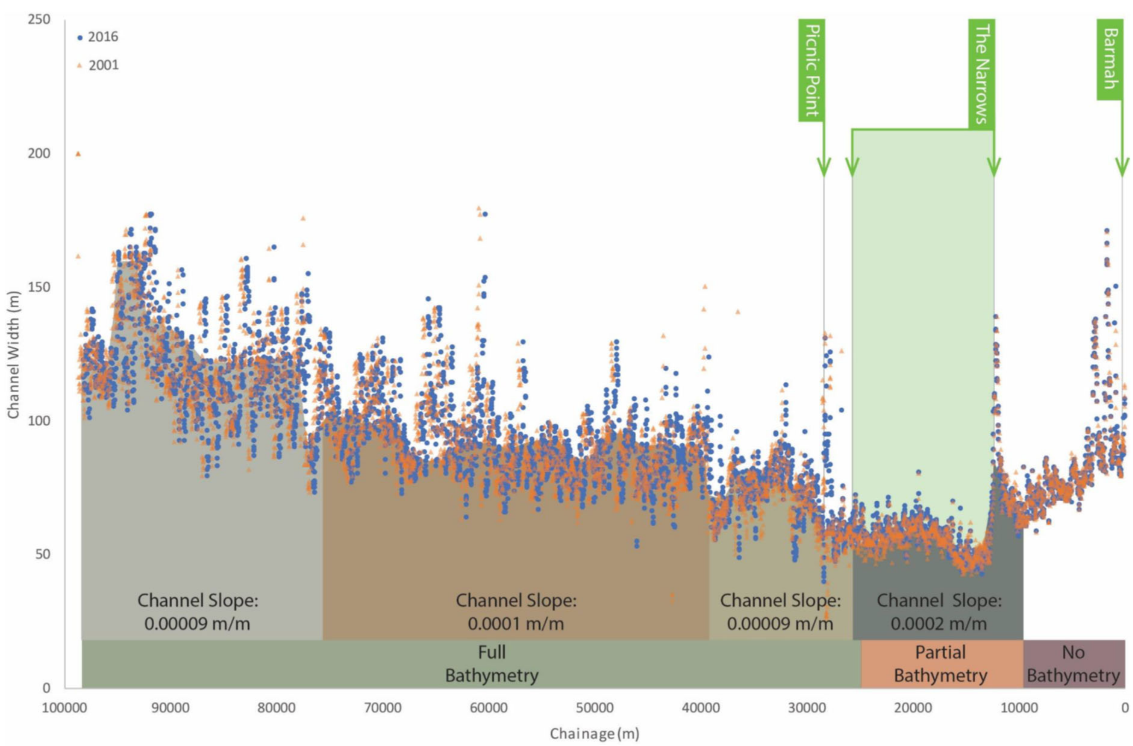

Figure 4-17. The change in channel widths between 2001 and 2016 based on LiDAR measurements. The channel slope and extent of bathymetric data are also shown. Chainage 0 is downstream and equates to River Murray chainage of 1760.6 km (Water Technology 2020).

4.2.3.2 Bank sediment

There is little pre or post regulation data on the sediment particle size composition of the riverbanks in this reach. Water Technology (2021) took samples of the riverbank sediment downstream of Bullatale Creek (**Figure 4-18**). The samples suggest that there are very low amounts of coarse sand and gravels in the riverbanks (**Table 4-5**). The exception was a sample taken from a sand lens (Bank Sample 104) that was not representative of the whole bank profile. Except for Sample 104, the dominant bank sediment sizes were fine sand and clays.

***Table 4-5**. Riverbank samples collected by Water Technology (2021) with the highest percentage size classes shown in bold and italics.*

Sample	Moisture Content (%)	Total gravel >2 mm (%)	Coarse sand 0.2 – 2 mm (%)	Fine sand 0.02 – 0.2 mm (%)	Silt 20 – 200 µm (%)	Clay < 2 µm (%)
Bank 001	5.9	0.3	4.1	30.1	30.1	***35.5***
Bank 002	3.4	0.2	1.8	***63.9***	16.4	17.7
Bank 003	1.1	0.1	12.2	***70.5***	10.7	6.6
Bank 004	3.8	0.4	8.1	32.8	14.5	***44.2***
Bank 005	2.7	0.0	1.0	***44.0***	37.3	17.6
Bank 006	2.8	0.0	1.8	***51.1***	28.9	18.2
Bank 104	1.3	0.2	***62.3***	25.9	2.9	8.7

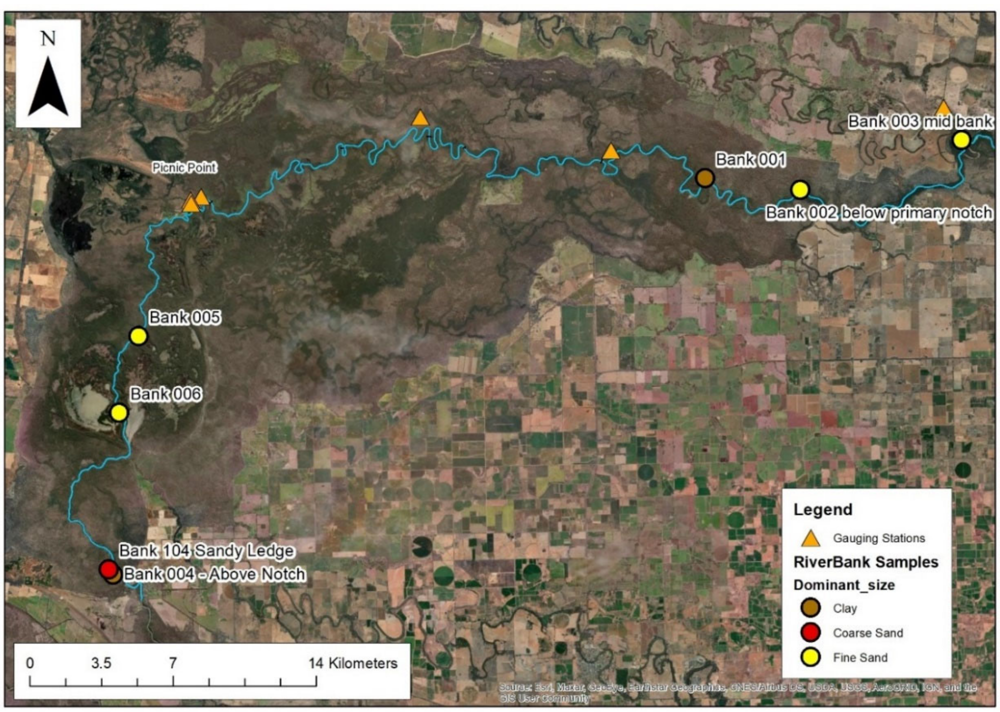

***Figure 4-18**. The locations and dominant particle sizes of the riverbank samples taken by Water Technology (2021)*

With Bank Sample 104 excluded, the coarse sediment did not show any clear trends in the downstream direction (**Figure 4-19**). There as a decline in the percentage of the bank samples that consisted of fine sand, but this was not a very consistent fining trend.

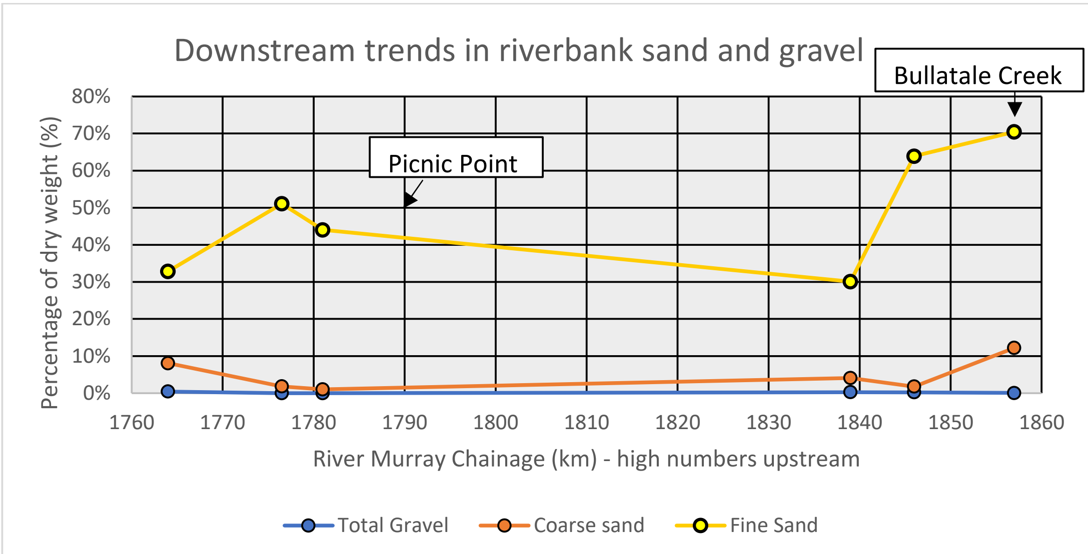

Figure 4-19. *Downstream trends in sands and gravel in riverbanks based on Water Technology (2021) data. The upstream extent of the survey was the Bullatale Creek, whilst the downstream extent was Barmah township. Picnic Point is at chainage 1790.*

4.2.4 Geomorphic changes observed in Reach 2

4.2.4.1 Changes in floodplain aggradation

Overbank deposition raises the elevation of the channel creating a meander belt on an alluvial ridge that can become elevated around the surrounding floodplain (**Figure 4-9**) (Baky 2018). Rutherfurd and Kenyon (2005) estimate background long-term depositional rates on the floodplain of 3 mm in 10 years and more recent historical ones of 7 mm in 10 years. More recent work by Baky (2018) has suggested slower rates of deposition of around 2 mm in 10 years.

4.2.4.2 Changes in bankfull width

From downstream of Bullatale Creek to Picnic Point the average differences in bankfull widths were +8 m (1876 to 1981) and +8 m (1981 to 2015). This gives rates of +0.08 m/yr and +0.2 m/yr respectively. The more accurate LiDAR comparison made by MDBA (2019) indicated that at the upstream end of the Barmah-Millewa Forest there was no significant change in bankfull widths between 2001 and 2016.

This would suggest that compared to Reach 1, which on average went from historical widening to more recent contraction, Reach 2 has had a modest increase in widening over time.

4.2.4.3 Changes in bankfull depth

Rutherfurd and Kenyon (2005) report the bankfull channel depths as 3.3-8 m in Reach 2, they do not suggest how these depths have varied over time. Water Technology (2020) used the 2017 bathymetric survey to determine bankfull channel depths from the Bullatale Creek confluence down to the Choke (**Figure 4-20**). These data show bankfull depths that vary between 2-5.5 m (excluding two low depth outliers). This suggests a decrease in the range of depths caused by aggradation, probably in the range of 1-2.5 m, compared to those reported by Rutherfurd and Kenyon (2005), however, there will be methodological differences.

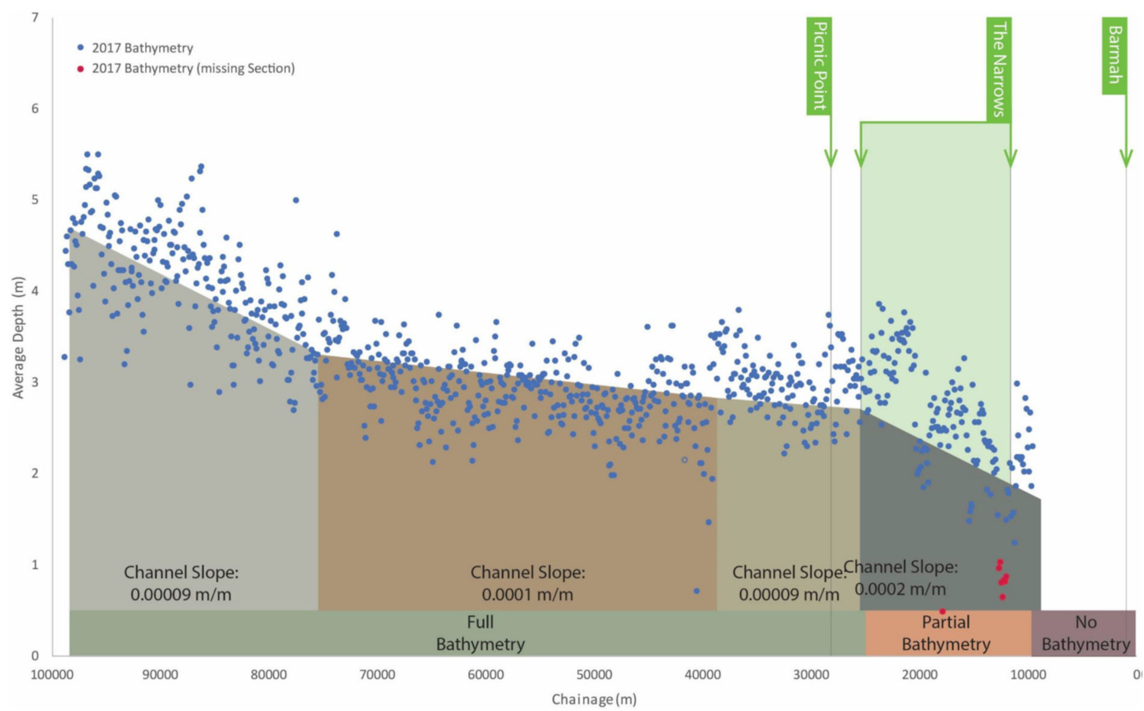

Figure 4-20. *Channel depths determined from 2017 bathymetric, plotted along with the average depth. The upstream extent of the survey is the Bullatale Creek offtake to the left of the figure. Chainage 0 equates to River Murray chainage 1760.6 km (Water Technology 2020 p. 36)*

Using a comparison of survey data Gower *et al.* (2020) showed that between the 1870s and 1976 the bed between Tocumwal and Echuca has aggraded on average by one metre; however, it was up to three metres in some places. They did not observe any clear trend in aggradation downstream. Whilst the overall trend during these time periods may be aggradation, there are suggestions that early periods of desnagging allowed channel incision to occur (Parliament of South Australia 1882 p.34), but this has not been quantified.

Hydraulic modelling between 1991-2020 by Gower *et al.* (2020) suggested that in a zone 26-38 km downstream of Tocumwal, which includes the Bullatale Creek offtake, there may have been on average 1.9 m of deposition. Further downstream in the zone between 71-93 km from Tocumwal, and just upstream of Picnic Point (94 km), they suggested there has been on average 0.8 m of deposition for the same period. These average rates of accumulation equate to 6.7 million m³ of bed sediment being deposited in Reach 2 in the last 30 years.

These modelled rates appear high when compared against the SPB data (SA 2020; 2021a; 2021b). When the SBP bed thicknesses were averaged over 10 km reaches they only suggested an average depth of 1.2 m downstream of Bullatale Creek (**Figure 4-21**) (**Appendix A1.4**). The 1.9 m in the last 30 years would be on top of any existing bed sediment, such as the average of 1 m sediment build up reported by Gower *et al.* (2020) from Tocumwal to Echuca. Despite differences in areas, an average of 1.9 m appears an overestimate.

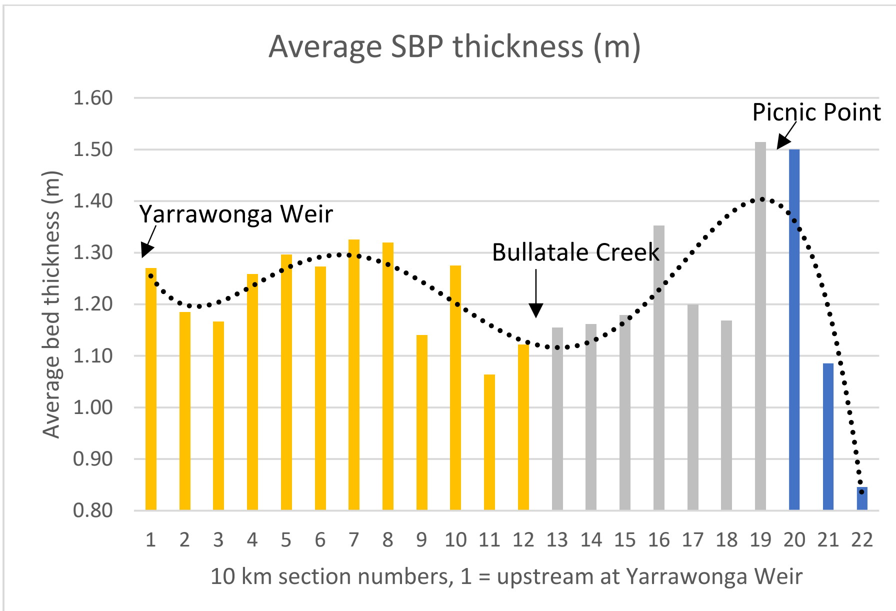

Figure 4-21*. The average thickness of SBP bed sediment calculated in 10 km sections of the riverbed. Section 1 starts at Yarrawonga Weir and Section 22 ends at Barmah township. Reach 2 (Sections 13-19) has been coloured grey. A 5th order polynomial trendline is shown in black.*

If 6.7 million m³ of coarse sand has been deposited in Reach 2, and it has also been transported downstream of Reach 2, then more than this volume must have come from Reach 1 upstream. This would mean that there has been over a 30 % reduction in the volume of bed sediment in Reach 1, which equates to an overall lowering of >0.5 m in the last 30 years. This appears to be a realistic amount of bed lowering, when compared to the difference between the armoured layer downstream of Yarrawonga Weir and the rest of the 10 km sections. However, if the armoured layer developed not long after the completion of Yarrawonga Weir in 1939, and the coarse sand bedload has been transported downstream since that point in time then there would be a much greater difference in elevations. Assuming the same rates of transport modelled by Gower *et al.* (2020) since 1939 to 2020, there would have been an average loss in bed depth of >1.4 m in Reach 1, or an overall export of over 18 million m³ of coarse sand out of Reach 1 and into Reach 2.

What is clear is that there has been aggradation downstream of Bullatale Creek reported both by survey differences between 1876-1976 and from modelling during the period 1991-2020. The build-up of sediment in Reach 2 would have reduced the bankfull channel depths and channel cross-sectional area. The rate of bed thickness increase could be in the range of 0.01 m/yr based on the survey data and a maximum of 0.06 m/yr based on modelling.

Table 4-6. Summary Box 3

- Reach 2 is a distributary fluvial system (DFS) that loses sediment transport capacity as effluents take flow away from the main channel. These systems naturally fill up with bed sediment, and this can cause avulsions to occur.
- Bed sediment has accumulated in the channel mainly around effluent junctions.
- The bankfull widths of 50 – 160 m have remained fairly constant since 1876 to 1981.
- Recent data collected on the bed and bank sediment shows that the bed was mainly comprised of coarse sand overlying a clay base, whilst the banks were mainly comprised of fine sands, silts and clays with a <12 % of coarse sand.
- The SBP data shows an average thickness of coarse sand of 1.2 m in the reach which equates to a volume of 7 million m^3.
- As with Reach 2 pools have nearly completely infilled resulting in coarse sand depths of over 4 m.
- Coarse sand grainsizes dominate the bedload all the way from Bullatale Creek to Barmah township.
- Rates of sediment build up on the riverbed may be between 0.01-0.06 m/yr.

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4.3 The pre-European riverbed sediment conditions for Reaches 1 and 2

The data on the current forms and processes, alongside historical information such as explorer accounts and early mapping can allow a general picture of the pre-European settlement bed sediment system. The two reaches will be considered together, meaning the bed sediment system can be broken into the following components:

1. Inputs from upstream
2. Inputs within the reaches
3. Outputs within the reaches
4. Outputs downstream
5. Contribution to reach bedload

Each of these components will be considered in turn to provide a point of comparison for current conditions.

4.3.1 Bed sediment inputs from upstream

The low stream power of the River Murray means that it is unlikely to transport high loads of sediment. Nanson and Knighton (1996) suggest that the bedload component was around 5 % of the total sediment load. The channel was, therefore, dominated by suspended sediment. Although there is no detailed record of the historic bedload flux from upstream, it can be assumed it was low and was mainly comprised of fine sand near to Picnic Point. An assumption based on the decreasing flows downstream through the Barmah-Millewa Forest means that the river would have had insufficient energy to transport coarse sediments. Modelling by NLWRA (2001) suggests that the reference load for bed sediment would be around 144,000 t/yr or 139,000 m^3/yr.

4.3.2 Bed sediment inputs within the reaches

Within the reach there were no major tributary inputs to contribute sediment. Bank erosion through lateral migration and effluent incision would have contributed fine sand sized sediment. It is unlikely that minor tributaries coming from the relatively flat catchment that surrounds the reaches would have the transport capacity to mobilize sand size or coarser sediment.

Low floodplain slopes, pre-disturbance riparian vegetation cover, and natural levees along the channel would also limit the amount of local overland flow mobilization of sediment into the channel.

4.3.3 Bed sediment output within the reaches

Effluent channels would have been at a range of elevations above the main channel bed. It is possible that they transported some riverbed sediment, however, there is no evidence to suggest this was a substantial volume. The observations by Pietsch & Nanson (2011) on the Gwydir River support this assumption, indicating a similar situation where limited bed sediment was transported out of the main channel by the effluents.

4.3.4 Bed sediment outputs downstream of the reach

The nature of this DFS means that outputs of bed sediment would be low through Picnic Point, with decreasing transport capacity moving downstream.

4.3.5 Contribution to reach bedload

Transient bedload storage would be in the channel on the bed and in bars. A very small component may have made it out onto the floodplain, probably because of effluent flows. An important consideration here is that the nature of this channel system is to aggrade sediment as the channel loses transport capacity downstream. It would, therefore, be expected that there would be a bedload component in a pre-disturbance state as bed sediment.

4.4 Summary

Moving downstream from Yarrawonga Weir to Picnic Point the River Murray changes from a wide and deep channel meandering channel with sandy point bars to a narrower channel that has multiple effluent channels. The main morphological changes occur as the channel crosses from a narrow floodplain (Reach 1) onto an ancient low angled alluvial fan (Reach 2). This part of the river system can be described as a distributive fluvial system (DFS), as unlike many rivers it loses flow in the main channel in the downstream direction.

This low energy system was dominated by fine (suspended) sediment and under natural conditions very low loads of sand it would be expected. However, the loss of flow by effluents occurred at multiple elevations above the bed of the River Murray. This meant that moving downstream towards Picnic Point the channel did not lose bed sediment into the effluents at the same rate as it lost flow. The result was a system that accumulated bed sediment in the channel. Over time this would have resulted in the channel becoming perched above the surrounding floodplain and creating a new channel or reoccupying a palaeochannel.

The natural, undisturbed, rate of sediment accumulation is unknown. However, it would be expected that as the channel downstream of Bullatale Creek aggraded sediment in the bed it would also have aggraded fine sediment on the floodplain to build an alluvial ridge. Recent estimates of the rate of floodplain aggradation in Reach 2 were 2 mm in 10 years (Baky 2018). It would be anticipated that rates of bed load accumulation should be slightly higher but in a similar order of magnitude. Whilst there would be pulses of sediment in the pre-European settlement channel, such as erosion after bushfires, it would be unlikely that these would be large in volume. This is because the transport capacity of the upstream catchment would have been much lower with smaller and less continuously connected tributaries.

The current channel has experienced a reduction in the volume of water than can be discharged through Picnic Point in the main channel (see section 1.3.2). Bathymetric surveys, sub-bottom profiler data, and bed sediment sampling have revealed:

- A riverbed comprised mainly of coarse sand.
- Sediment depths on the bed of on average 1.22 m, from Yarrawonga Weir to Picnic Point.
- Dunes on the bed with a height of 0.5 – 1 m.
- Infilling of meander pools by over 4 m of bed sediment.

Whilst the presence of sand was expected, the depth of infilling of meander pools, sizes of dunes, and depth of mobile sediment was not. These features suggest that the rate of aggradation of bed sediment has been greater than in the pre-disturbed setting. In the rest of this report, the volume of sediment that is greater than the pre-disturbance reference will be termed excess bed sediment.

Based on the history of anthropogenic disturbances and the data on channel change four questions have been posed to explore the accumulation of bed sediment. The accumulation could be the result of an increase in sediment supply, a decrease in transport capacity, or a combination of both. The questions posed range from the simplest to most complex combination of processes to explain the current state of sediment on the channel bed.

1. Has the coarse sand bedload come from recent flooding?
2. Was regulation responsible for erosion that deposited coarse sand on the bed?
3. Did land-use change, including historical gold mining, supply the coarse sand bedload?
4. Could desnagging have increased the bedload supply of coarse sand and its mobility?

For each of these disturbances the: (1) sources of bed sediment, and (2) processes that affect bedload transport rates will be reviewed. Of course, a combination of these factors could have been involved.

5 Has the coarse sand bedload come from recent flooding?

5.1 Hypothesis

Flooding often leads to high sediment loads of both bedload and suspended sediment. A flood can also cross a geomorphic threshold changing the form of the river, such as straightening or creating a new channel on the floodplain (avulsion). These dramatic changes can alter the way sediment is mobilized into the channel and may trigger greater volumes of sediment to be eroded in subsequent lower flows.

One hypothesis may be that a recent flood, or a period of increased flooding has produced some, if not all, of the sediment in the bed. These elevated discharges could both erode and mobilise sediment and may result in local sediment storage that exceeds the transport capacity of the Choke for a period of time.

To understand what constitutes a period of high flows, or a large flood event, historical discharges need to be examined to set context for the recent record. Regulation has altered the timing and magnitude of flows, however, flooding especially large over 1:20 year events still occur. For this section just the timing of large flood events will be considered, the influence that regulation has had on other flow and channel characteristics will be outlined in more detail in section 6. However, we will only be considering Reaches 1 and 2, in the sediment supply area 3, for this hypothesis as bed sediment should be mainly supplied within this reach during recent flooding because of the influence of Lake Mulwala.

5.2 Historic hydrology

The hydrology of the Murray has been modelled by Gallant and Gergis (2011) to extend the record back to 1790 (**Figure 5-1**). Both flood and drought periods can be observed, especially in the decadal mean inflows (**Figure 5-1b**). Periods of drought are the flipside to the periods of high flows. A prolonged drought may accumulate stores of sediment, such as those from sub-aerial processes such as desiccation of the riverbanks (Couper 2003). If a drought is followed by significant flooding that is not mitigated by regulation, then this may be the period of highest bed sediment flux.

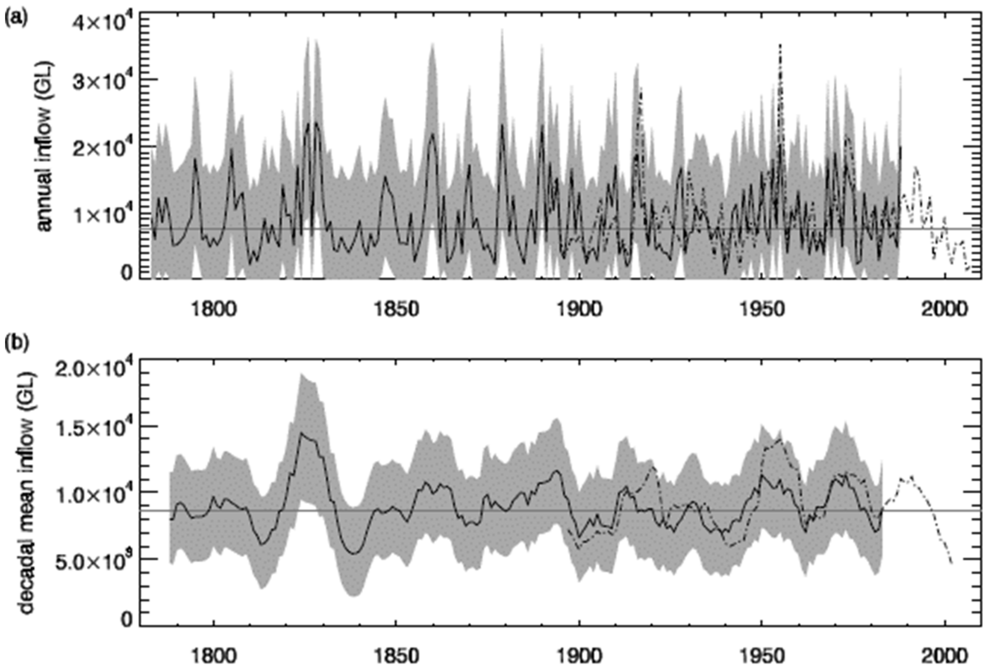

Figure 5-1. *Paleo reconstructions of (a) annual and (b) decadal River Murray streamflow. The grey envelope is the confidence interval, 2 standard deviations of the combined calibration and residual errors. The black solid line is the median of the ensembled reconstructions, and the dash-dotted line shows the observed River Murray streamflow from 1892 to 2008. Thin grey lines are the medians of reconstructed annual and decadal reconstructed stream flows from 1892 to 1988, 7838 and 8744 GL respectively. (Gallant & Gergis 2011, p. 7)*

The most recent drought from 2017 to 2019 (**Table 5-1**) had record low rainfall, significantly lower than that observed during the original records set during the Federation Drought around 1902.

Based on an analysis of the river gauge at Tocumwal, which has been operational since 2nd January 1908 the highest flood on record was in 1975 (**Table 5-2**). Records at the Echuca Wharf gauge suggest the highest flood to have been in 1870 (Echuca Historical Society 2020).

The 5th highest flood on the Tocumwal record was in 2016. This event was not during a particularly wet period, and since the flood the flows have remained consistently low (**Figure 5-2**) including the drought from 2017 to 2020. Prior to 2016 the 6th largest flood event on record was 23 years earlier in 1993.

Table 5-1. *Major droughts in SE Australia adapted from the ABS (1988) and BOM (2021).*

Drought period	Affected area	Average duration and month of break	Descriptive remarks
1888	Southern Queensland, most of New South Wales, Victoria, South Australia and parts of Tasmania	9-10 months to January 1889	In parts of northern New South Wales, not broken until autumn 1889
1902	New South Wales, Victoria, parts of southern Queensland, South Australia and Tasmania	Victoria, South Australia and Tasmania: 9 months to December 1902 New South Wales and southern Queensland 12 months to 1902	Considerable overlapping of affected areas
1914-15	Victoria, New South Wales west of the tablelands, settled areas of South Australia and most of Tasmania	South Australia 11-12 months to June 1915 Northern Victoria and New South Wales 10-12 months to June/July 1915 Southern Victoria 16 months to May/June 1915	Rainfall during 1913 also below average in parts of south-eastern Australia; and much of Victoria and western New South Wales had some relief in the summer of 1914-15
1940-41	Most of New South Wales, Victoria, South Australia and eastern Tasmania	South Australia 6 months to January 1941 Tasmania 8-9 months to January 1941 Victoria 11 months to January	Variable durations in New South Wales
1944-45	Most of New South Wales, Victoria and South Australia	South Australia and south-western Victoria 4-6 months to summer 1944-45 Southern Victoria 12 months to August 1945 Northern Victoria and southern New South Wales 15-19 months to August 1945 Northern New South Wales 15-17 months to June 1945	Well below average rainfall in parts of South Australia in April-June 1945; and 1943 was also a dry year in parts of south-eastern Australia
1967-68	Victoria, southern New South Wales, South Australia and Tasmania	South Australia 12-13 months to March 1968 Tasmania 15-16 months to May 1968 Victoria and New South Wales 14-15 months to May 1968	Other extensive parts of Australia affected during 1958-67
1972-73	Most of Victoria, western and central New South Wales, South Australia and north-eastern Tasmania	9-10 months ending February 1973	Drought broke in February 1973; except in north-eastern Tasmania, where it broke in autumn 1973
1982-83	Victoria, most of New South Wales, South Australia, southern Queensland and Tasmania	Generally 11 months ending February 1983 Tasmania: 9 months ending February 1983	Drought broke in autumn 1983
1997-2010	Victoria, most of New South Wales, South Australia, southern Queensland, Southern Western Australia and Tasmania		Drought broke autumn 2010
2017-2019	East Victoria, most of New South Wales, South Australia, western Queensland, Western Australia and eastern and northern Tasmania		Near to above average rainfall returned to many parts of Australia from January 2020 onwards.

Table 5-2. Floods over 150,000 ML/d at Tocumwal (02/01/1908 to 24/04/2020).

Year	Month	Day	Discharge (ML/d)	Rank
1917	07	26	190,825	2
1931	06	30	162,074	7
1955	08	30	157,804	9
1956	07	11	183,249	4
1970	09	03	161,664	8
1974	05	19	183,362	3
1975	10	30	238,231	1
1993	10	8	175,764	6
2016	10	8	177,123	5

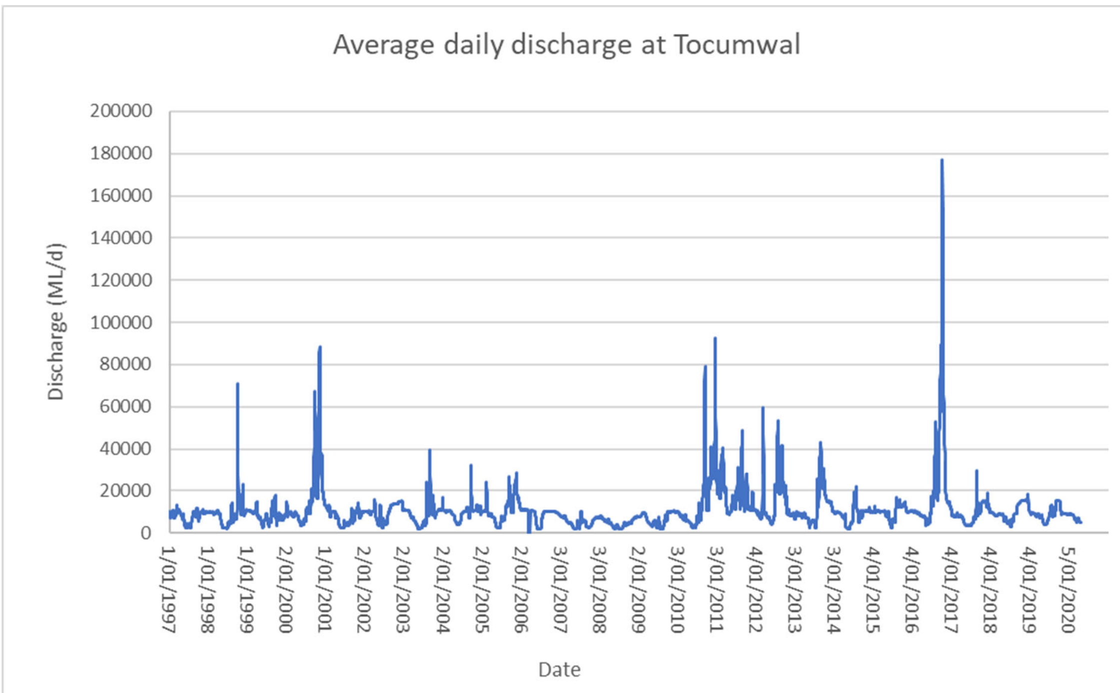

Figure 5-2. Average daily discharge at Tocumwal from 01/12/1996 to 18/06/2020.

5.3 Changes in the sources of bed sediment from recent flooding

There is no evidence to suggest that recent flooding has caused a threshold change in the channel that would mobilize more coarse sediment from Yarrawonga Weir to Picnic Point. No major channel changes have been observed such as the avulsion of the channel or a change in sinuosity that would liberate a potential source high in coarse sand. The low percentage of coarse sand in the riverbanks (**Figure 4-19**) mean that relatively high rates of channel erosion would be needed to supply even a small proportion of the >20 million m^3 measured on the riverbed.

5.4 Changes in the processes that affect bedload transport rates from recent flooding

There appears to be a reduction in the frequency of climatically driven flooding, excluding the influence of regulation. Longer drier periods without flooding reduce not only the downstream transport of existing bed sediment in the reach but also any opportunities for connection with any long-term stores such as upper sections of point bars, the floodplain or into effluent channels.

5.5 Conclusions

There appears to be little evidence to suggest a large flood, or series of floods, has recently produced and transported substantial volumes of coarse sand in the reach. It is perhaps better to consider the influence of long periods of drier conditions. During a prolonged period of lower flows there would be little opportunity for bed sediment to reach longer term stores such as the upper areas of point bars or floodplains. The lack of connection with longer term storages and a high volume of mobile bed sediment in the reach may have been sufficient to unbalance the equilibrium in the system.

It could be that rather than floods mobilising the sediment, continual in-channel flows may be sufficient to slowly move sand downstream into lower and lower stream power reaches, aggrading the lower part of the reach just upstream from Picnic Point. This might explain some of the distribution of sediment in the channel, but it does not really address the volume of sediment.

Table 5-3. Summary Box 4

- Decadal wet and dry periods have been experienced in the River Murray, these have been modelled to extend the record back to 1790.
- The last major flood event in 2016 was the 5th highest on record at Tocumwal.
- The last drought was the Millennium Drought between 2017 and 2019.
- Since 1997 the conditions have been reasonably dry only punctuated by the one major flood event in 2016. These conditions appear drier than the historical record since 1780.
- These drier conditions could allow a build-up of sand-sized sediment in the main River Murray channel, with little opportunity for other longer-term sediment stores to be engaged, such as upper point bars or floodplains.
- Rather than flooding increasing the sediment loads, it may be that the continued low flows have reduced the rate of flux of bed sediment out of the channel.

6 Was regulation responsible for erosion that deposited coarse sand on the bed?

6.1 Hypothesis

The reach has been changed to allow the efficient transfer of water for irrigation and environmental watering purposes, and to reduce flooding. To do this the following methods have been used:

1. Construction of reservoirs and weirs.
2. Artificially elevating levees along riverbanks.
3. Regulating offtakes and effluents.
4. Changing the timing and stage of discharge.

All these anthropogenic measures have altered the amount of sediment entering the system, its conveyance along the River Murray, and its storage. This section will explore whether these alterations could have resulted in the current channel bed conditions of deep mobile bed sediment that has infilled pools. The contradiction that regulation could both erode more sediment and result in greater rates of deposition will be specifically addressed.

6.2 Sediment trapping by impoundments

The building of Hume Dam and Yarrawonga Weir has changed the continuum of sediment movement downstream. The river has been changed from a continuous channel to one with two large barriers (Hume Dam and Yarrawonga Weir) downstream of large lakes. When sediment enters a lake the velocity of the water transporting it decreases and it starts to settle out. The trapping efficiencies of suspended sediment have been estimated by Thoms & Walker (1992) as 35 % for Lake Hume and 52 % for Lake Mulwala. Tilleard *et al.* (1994) calculated that the suspended sediment trap efficiency of Hume reservoir using various methods and provide a range of estimates between 90-97 %.

Using the Brune (1953) curves of sediment trapping vs. residency time (reservoir capacity = 117,500,000 m^3/average annual inflows = 3,129,569,000 m^3/yr) a trapping efficiency of around 85 % has been estimated for Lake Mulwala in this study. The finer sediment is likely to be the component that is passed downstream and not trapped. It will be assumed for this study that the bed sediment is likely to have an almost 100 % trap efficiency for both reservoirs.

The sediment that is deposited in the reservoir is an indicator of the amount of sediment that is being transported by the river. Thoms & Walker (1992) estimate the deposition of 1.47 million tonnes in Lake Mulwala and Lake Hume between 1974 and 1989. Ronalds (1950) calculated the total siltation in Lake Hume from 1932-1945 to be about 6,000 acre feet or 7,400,880 m^3 (569,298 m^3/yr). This volume represents 0.005 % of the capacity of the reservoir or an average of less than 2 ¼ inches (5.7 cm) over the whole of the 33,000 acres covered by the reservoir. The average rate of reservoir capacity loss by sedimentation for

Australia and Oceania was determined to be 0.94 % (Basson 2009) or 0.81 % globally. This means that the 0.005 % loss of capacity by sedimentation in Lake Hume is low by both continental and global standards, Davis *et al.* (1997) came to the same conclusion.

Low sedimentation rates in Lake Hume have been confirmed by Baldwin *et al.* (2008) who concluded:

1. Rates of sedimentation in Lake Hume are generally quite low (<3 mm year in the western area of the reservoir) and are consistent with rates expected from a mostly forested catchment.
2. Most of the sediment entering Lake Hume comes from the River Murray catchment, but there is some uncertainty on where in the catchment the sediment actually comes from.
3. There are elevated levels of arsenic, nickel and chromium in the lake's sediments. It is suggested that the arsenic and nickel are associated with historical mining activity in the immediate vicinity of the lake while chromium may come from a yet unidentified chromium deposit in the Mitta Mitta River catchment.

In terms of bed sediment trapping, we would expect that as the coarser sediment, including sand, moves from the flowing river to the near static lake where it would rapidly be deposited. The coarsest fraction would drop out first at the head of the reservoir. If there were sufficient sediment loads a delta would prograde out into the storage. There is no clear evidence of this occurring in either Hume or Mulwala based on observations of current aerial photographs and a 1999 survey of Lake Mulwala (Water ECOscience 1999). However, this may be influenced by the varying lake levels during extended periods of high and low inflows causing the sediment to drop out over an extended area. This would cause a less distinct delta and more of it could be underwater during medium to high lake levels.

These observations all suggest that no sand sized sediment is getting through Lakes Hume or Mulwala. As there are no large tributaries between Yarrawonga Weir and the Choke, the sand that is currently in Reaches 1 and 2 has either come from:

1. Upstream of Yarrawonga Weir before 1939.
2. Sources within Reaches 1 and 2 combined with bed sediment supplied upstream of Yarrawonga Weir before 1939.
3. Sources within the Reaches 1 and 2 after 1939.

6.3 Clearwater scour

The trapping of sediment in the reservoir results in discharges downstream having low sediment concentrations (Marren *et al.* 2014) (**Figure 6-1**). Immediately downstream of the impoundment there may be the potential for greater entrainment of sediment because of the low loads. This process is known as clearwater scour. The increased rate of erosion can lead to channel enlargement downstream of impoundments, especially those with high trap efficiencies. The length of impact is partly controlled by the distance to the next tributary input that supplies a significant load of sediment. In the case of the Hume Dam the Kiewa River enters only 15 km downstream and so the effect length may be shorter than for Lake Mulwala, where there are no major tributary inputs until the Lower Broken Creek River 183 km downstream. Brandt (2000) suggests the area of maximum erosion would be around 20 channel widths downstream, in the case of Yarrawonga Weir this would be around 140 m in width x 20 = 2,800 m.

A reduction in flows downstream of an impoundment, because of irrigation or flood mitigation, can then result in an area of enhanced sediment deposition downstream of the clearwater scour as there are no longer the same flows to convey the sediment (Marren *et al.* 2014). The changes in flow regimes downstream are summarised in **Table 6-1**. They indicate an increase in frequency and duration of lower in-channel flows and a decrease in number and frequency of larger flood events. If these flow variations on the Murray have changed the flux of bed sediment, we would expect to see region of channel enlargement downstream of Hume Dam or Yarrawonga Weir, there may then be an area of increased deposition even further downstream. For Yarrawonga Weir these areas of sediment starvation and enhanced deposition may be around 3 km and >3 km respectively.

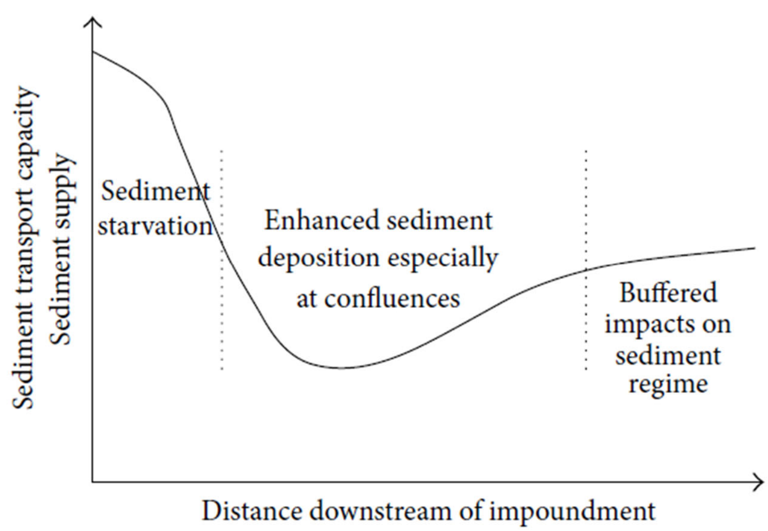

***Figure 6-1.** Conceptual model of the changes in sediment regimes downstream of dams. The x-axis represents distance downstream from the impoundment, with the area of sediment starvation beginning immediately downstream of the dam wall. y-axis represents sediment supply and transport capacity. Vertical dotted lines mark the transitions between downstream reaches dominated by different processes. The effect lengths downstream vary highly based on the position of tributary inputs (Marren et al. 2014).*

Table 6-1. *Summary of the effects of regulation on flow characteristics downstream of Yarrawonga Weir (Roberts 2006 cited in GB CMA 2013).*

	Flow thresholds at Tocumwal ML/d					
	=>12,000	=>15,000	=>20,000	=>30,000	=>40,000	=>50,000
Frequency	Increased	Similar	Decreased	Decreased	Decreased	Decreased
Length (mean duration)	Decreased	Decreased	Decreased	Similar	Similar	Similar
Variation (CV)	Increased	Increased	Increased	Similar	Increased	Increased
Small vs. large events (skew)	Increased	Increased	Increased	Similar	Similar	Decreased
Number of floods starting in May-June	Decreased	Decreased	Decreased	**Greatly decreased**	**Greatly decreased**	Decreased
Number of floods starting in Sept-Nov	**Greatly increased**	**Greatly increased**	Decreased	Decreased	Decreased	Decreased

Air photos from 1945-1950 from Barmah upstream to the junction of the Ovens River have been georectified for this study to investigate any signs of planform channel enlargement as a result of clearwater scour. This period was just after the Yarrawonga Weir construction and would be expected to have some signs of clearwater scour if it were occurring.

The black and white air photos indicate lower vegetation cover on the landscape, probably because this was not long after the WWII drought. This would suggest that with reduced vegetation cohesion surface sediment would be more erodible. Directly downstream of the weir there are very limited sandy deposits compared to further downstream. One possibility is that near the weir there had been erosion that was then deposited downstream to create a sandier environment, or alternatively the reference condition is for sandy deposits and these have been eroded away near the weir. As the sandy point bars have been described historically in this area it is more likely the latter.

It does appear as if there was more sediment in the channel and on the point bars downstream of this zone of potential erosion. It is difficult to determine the extent of depositional features because surface reflectance on the water is similar in colour to sand deposits (**Figure 6-2**). The region around 8-40 km downstream of Yarrawonga Weir appears to have more sandy material in 1945-1950 than currently (**Figure 6-3**). Without other measurements it is difficult to interpret what this may mean for the transport of sand in this section. It could suggest this might have been a region of enhanced deposition of upstream erosion or it could mean increased transport of sediment on the bars from more rapid lateral migration.

Tilleard *et al.* (1994) compared surveyed cross-sections between Hume Reservoir and Albury on the main channel between 1977 and 1992. Their calculations indicated that the riverbed has deepened by as much as 24 % since 1977. It is unclear what depths they are referring to; however, they suggest the channel is between 5-9 m deep. If we take 9 m as the maximum area of deepening this would be a change from 7.26 m to 9 m, or 1.74 m of deepening.

Figure 6-2. *1949-1950 aerial photos of the River Murray directly downstream of Yarrawonga Weir.*

Figure 6-3. *Current imagery from ArcGIS directly downstream of Yarrawonga Weir.*

Specific gauge data was available from January 1970 to August 2020 from the River Murray gauges at Yarrawonga Weir Downstream (**Figure 6-4**) and Tocumwal (**Figure 6-5**). MDBA (2009) identified two major flow levels for regulated releases Level A at around 10,600 ML/d and Level B between 11,000 and 11,700 ML/d during 1980-2006. Level B flows do not occur after 1995, so the specific gauge data was filtered to look at the Level A flows using discharges from 9,800 to 10,990 ML/d.

The trend at Yarrawonga Weir Downstream gauge is for a decreasing stage for the filtered discharge range. This trend has a high coefficient of variation of $R^2 = 0.88$ suggesting a significant linear decrease over time. An increase in channel capacity by channel incision, channel widening, or both can create the conditions where the stage decreases for a given discharge. Clearwater scour is highly likely to be responsible for these changes. If clearwater scour has created an armoured bed layer near Yarrawonga, as suggested by Gippel and Lucas (2002), then it is more likely that the increased capacity since the armoured layer developed has been the result of channel widening rather than deepening. The SBP depth and acoustic profile (SA 2021a) shows a relatively planar bed surface without the dunes observed downstream. This also suggest that an armour layer has been produced that protects coarse sand beneath it from erosion.

At Tocumwal a similar trend of decreasing stage for the same range of discharges also occurs but it has a much lower slope and coefficient of variation ($R^2 = 0.3669$). This would suggest that there is less consistent channel change at this site. Some of the variability may be due to pulses of bed sediment moving along the bed, such as the increase in stages between 1993-1994. These increases in stage for the specific range of regulated discharges occurred after periods of higher discharges (**Figure 6-6**). This would suggest that during these wet periods there were higher volumes of sediment in the bed that were transported away during drier periods. If the overall declining trend is real, then this may indicate that there is an evacuation of sediment from this site as a result of reduced bed sediment inputs upstream.

If all the change in specific gauge levels was attributed to bed lowering this can be used to estimate the maximum rates of lowering at Yarrawonga Weir and Tocumwal in Reach 1. Incision of around 0.6 m at Yarrawonga Weir between 1970-2020 would produce a rate of 0.012 m/yr at Yarrawonga Weir (**Figure 6-4**). A lowering of the bed by around 0.25 m at Tocumwal from 1974-2020 results in a rate of 0.005 m/yr (**Figure 6-5**).

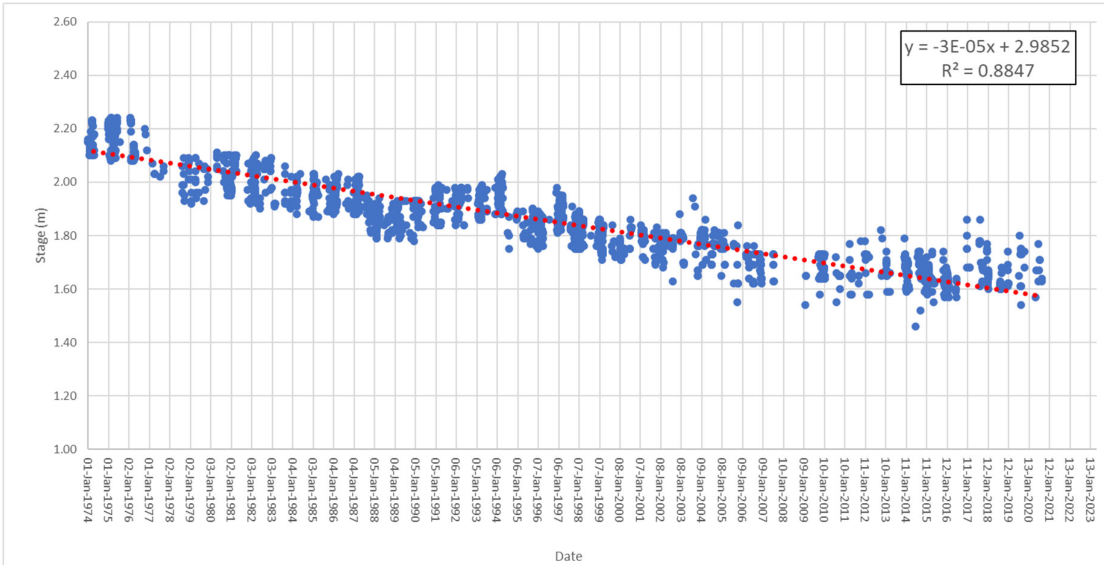

Figure 6-4. Yarrawonga Weir Downstream gauge showing the stages of discharges between 9,800 to 10,990 ML/d from Jan 1970 to August 2020.

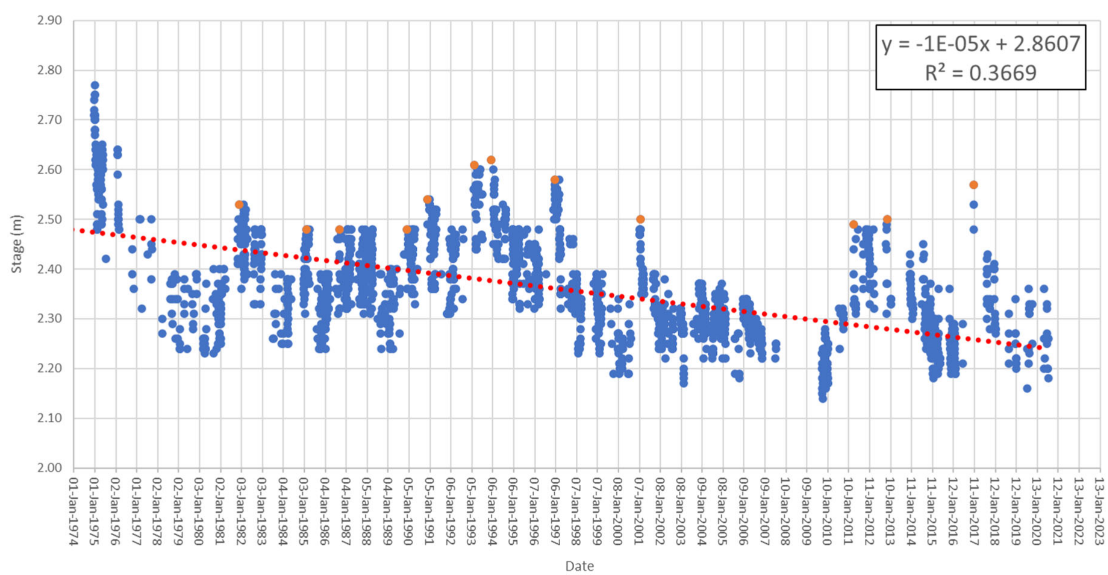

Figure 6-5. Tocumwal gauge showing the stages of discharges between 9,800 to 10,990 ML/d from Dec 1974 to August 2020. Points shown in orange are those where there has been a large change in stage after a period of lower stages.

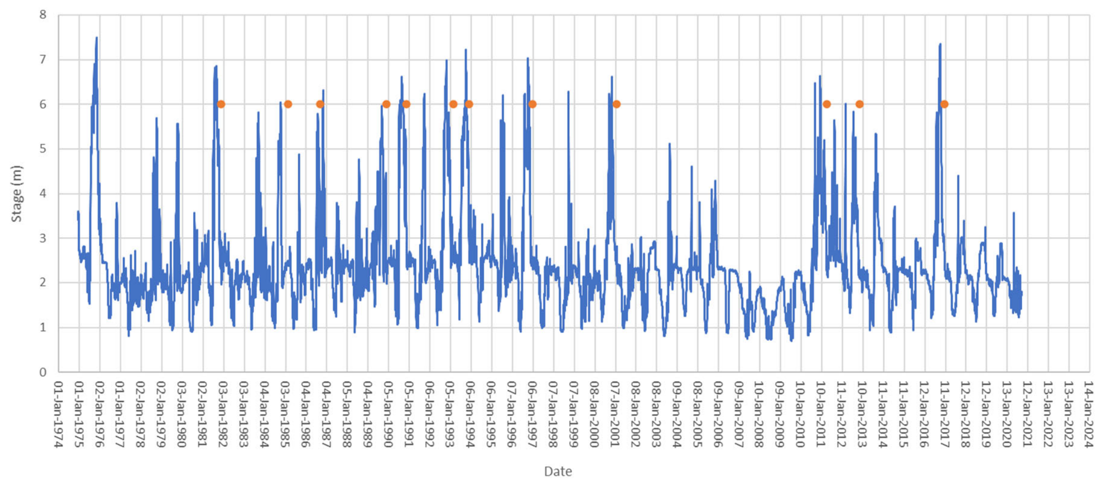

*Figure 6-6. Points of large stage changes from **Figure 6-5** plotted as orange points on the complete record of stages from Dec 1974 to August 2020.*

Assuming that the incision of the bed has also caused bank widening, then some of the widening reported by Rutherfurd and Kenyon (2005) (**Figure 4-6**) may be as a result of increased rates of erosion from regulation. This may be both from clearwater scour and from a change in the timing and frequency of high in-channel flows. The exact volumes of sediment released, and the likely sediment size distribution of the bank material upstream of Bullatale Creek are unclear. However, the volume of coarse sand from bank erosion between Yarrawonga Weir and Picnic Point was estimated based on changes in channel width from 1876 and 2015 (**Appendix A2**) and the available riverbank sediment grainsize data (**Table 4-5**). The estimated volume of coarse sand from bank erosion was approximately 2.3 million m^3. This is much less than the >20 million m^3 of coarse sand estimated to be on the riverbed over the same length of channel.

6.4 Artificial levees

Levees have been constructed along the River Murray from at least the 1870s (Rutherfurd & Kenyon 2005). They initially protected from flooding and then allowed more effective distribution of water for irrigation. Often, they enhance an existing levee that would have been the product of natural processes.

The Argus newspaper in 1898 suggested that a levee was being planned from Cobram down through the Barmah Forest.

"There are now at work along the bank of the River Murray, below Cobram, on the Victorian side, two survey parties, the members of which are engaged taking levels or the construction of a levee to keep back the flood waters. It is intended to utilise the unemployed labour of Melbourne on a large scale in the work of reclamation. About three years ago a levee, several miles in length, extending from below Cobram, down stream, was constructed, and has been the means of adding an additional areas of first-class wheat growing land to the district. The surveys now being made will extend from about the eastern boundary of the parish of Strathmerton, down to the Barmah Forest, and through the parishes of Strathmerton, Ulupna, Yalca, Yeilima, and Barmah, a distance of nearly thirty miles. It is estimated that about 100,000 acres of first-class land can be reclaimed, there being about 50,000 acres in the Barmah and Yeilima forests." (The Argus 1898 p.7)

It was reported in 1899 (The Age 1899) that the Forestry Commission wanted to make an alteration to the route of the levee. However, the final decision could not be established from the literature.

"The levee at its western end is, however, held by the Forest Commission to cut too deeply into the Barmah forest, which contains some of the best of the small supply of red gum timber now left in the colony". (The Age 1899 p.9)

Water Technology (2013) undertook an assessment of the levees along the River Murray from Cobram to Barmah (**Figure 6-7**). From this assessment they determined the average recurrence interval (ARI) that the levee would contain in the area upstream of the Barmah Forest and the floods that would be contained downstream. The 1975 flood, that was the largest on record on the Tocumwal Gauge, was assessed relative to the levee heights to see where it would have spilled (**Figure 6-8**). Water Technology (2013) estimate the 1975 event to have a 20-30 year ARI at Yarrawonga and Tocumwal and a 10-20 year ARI at Barmah.

Upstream of Tocumwal the levees frequently contained the 100 year ARI along their extent. Downstream of Tocumwal anything above the 20 year ARI would spill onto the floodplain. There is then a short reach until Kynmer Creek effluent that would have contained the 1975 event. This levee distribution suggests that there may have been reduced floodplain connection from Cobram downstream, however there should still have been connection that resulted in sediment deposition near to Tocumwal and downstream of Kynmer Creek. This means that although levees have contained the flow and increased the transport efficiency of the bed sediment there are discontinuities through the reach that may allow some connection of coarser suspended sediment out onto the floodplain. This is unlikely to be coarse sand and more likely to be silts and clays with a small proportion of fine sand.

Figure 6-7. *Map of River Murray showing the ARI contained by levees upstream of Barmah Forest and the year of floods contained downstream (Water Technology 2013).*

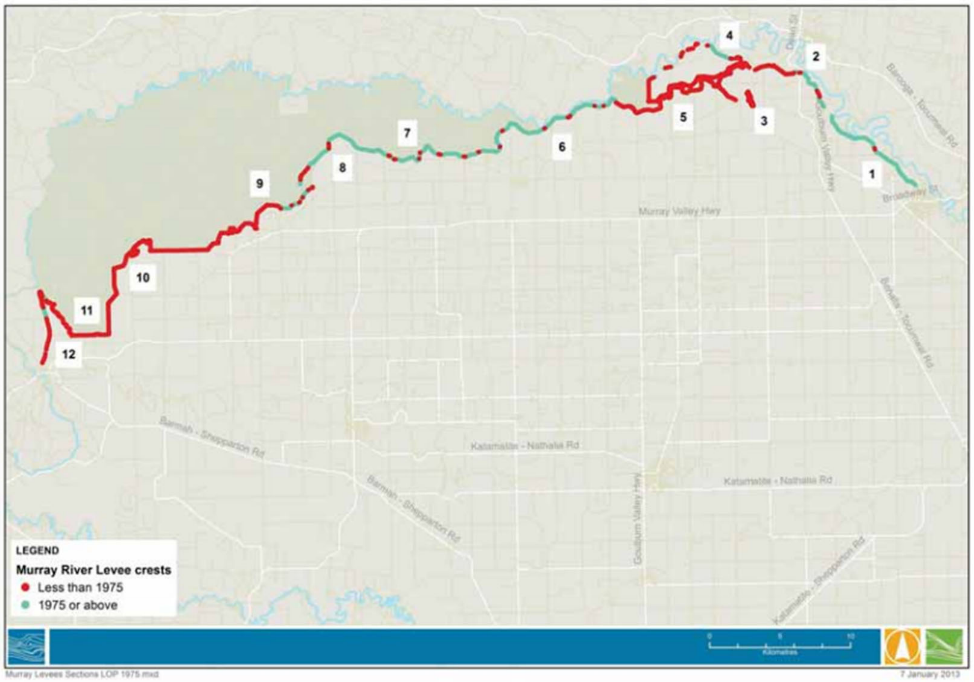

Figure 6-8*. Map of River Murray showing the levees upstream of Barmah Forest and whether they contained the 1975 flood (Water Technology 2013).*

6.5 Regulated effluents

More than 50 water management structures exist within the Barmah–Millewa icon site. Most of the larger structures were built in the late 1930s following regulation of the River Murray to prevent water loss from the regulated river into the Barmah–Millewa Forest. More recently, many smaller structures have been constructed to re-permit flow into previously blocked creeks or into areas where improved water management for the wetland system ecology has been identified (DSE & GBCMA 2005).

An example of the operation of the regulators is shown in **Table 6-2**. This shows that the distribution of both water and sediment is now highly controlled within the Barmah-Millewa Forest. These regulators are closed during the period of irrigation delivery during the summer and autumn, unless there is a rainfall rejection event, or an environmental flow. Prior to regulation as the river stage increased effluents would connect and flow would disperse across a wide area of wetlands. This process would have resulted in the deposition of sediment out across the floodplain, with higher rates around the effluents. The deposited sediment would have mainly been the suspended load, but Thoms *et al.* (1999) found fine sands in overbank deposits in the Barmah-Millewa Forest pre- and post-1954 suggesting that this size faction has been transported out of the channel. Pre-regulation there would have been lower sediment fluxes reaching the Choke than in the current regulated environment if there were losses of the fine component of the bedload out of the effluents.

The effluents sat higher than the bed of the River Murray, but some of them may have been artificially incised to allow water to be redistributed for irrigation. At their present level they are highly unlikely to take significant bedload.

Table 6-2. *The operational characteristics of regulators in the Barmah-Millewa Forest during seasonal and unseasonal floods (MDBA 2012).*

River Murray flow at Yarrawonga (GL/d)	July to mid-December		Mid-December to May	
	Regulators to be opened	Water management area affected	Regulators to be opened	Water management areas affected
11	Victoria • Gulf Creek (partial)	• Gulf	Victoria • tertiary regulators • Sandspit • Boals • partial Bull Paddock • partial Stewarts Kitchen	• Boals Deadwood • partial Top Island • Tongalong Creek • Towong water management area
	New South Wales • Mary Ada	• Mary Ada	New South Wales • Mary Ada (partial)	–
12	Victoria • Sandspit • Bull Paddock, Stewarts Kitchen • 25% Gulf	• Smiths • Gulf • northern Barmah (except Boals) • Edward, Moira and Aratula	Victoria • tertiary regulators • Sandspit • Boals • partial Bull Paddock • partial Stewarts Kitchen	• Boals Deadwood • partial Top Island • Tongalong Creek • Towong water management area
	New South Wales • Mary Ada • selected others (depending on duration)	–	New South Wales • Mary Ada • selected others (depending on duration)	–
13	Victoria • Sandspit • Bull Paddock • Stewarts Kitchen • 50% Gulf	• Smiths • Gulf • northern Barmah (except Boals) • Edward • Moira • Aratula	Victoria • all except for minimal Gulf	• all (minimal Gulf) • Towong, increasing to most other water management areas
	New South Wales • Mary Ada • selected others (depending on duration)	–	New South Wales • Mary Ada • selected others (depending on duration)	–
14	Victoria • All, except Boals Deadwoods	• all, except parts of Boals Deadwood • Edward • Moira • Aratula • Plantation • Towong • St Helena	Victoria • all, with more Gulf	• all (moderate Gulf) • Towong, increasing to most other water management areas
	New South Wales • Mary Ada • selected others (depending on duration)	–	New South Wales • Mary Ada • selected others (depending on duration)	–
≥15	all regulators open (Gulf and Mary Ada progressively opened greater up to 25 GL/d)	all	all regulators open	all

6.6 The effects of changing the timing and stage of discharge on bed sediment fluxes in the reach

The discharges from Yarrawonga Weir are now a seasonal reversal of flows compared to those that would occur naturally (**Figure 6-9**). Lake Mulwala now effectively has two seasons. The irrigation season from mid-August to mid-May and the rest of the time is a winter season. During the irrigation season the channel is reasonably full for much of the time. During the winter season Lake Mulwala may be drawn down for maintenance or to a level that means there is accommodation space for flood events that may come from the Ovens, Kiewa and Murray. During the irrigation season if a large rainfall event occurs that cannot be stored by Lake Mulwala there will be a rain rejection event that floods the Barmah-Millewa Forest. These floods can be unseasonable for the natural flooding of the forest.

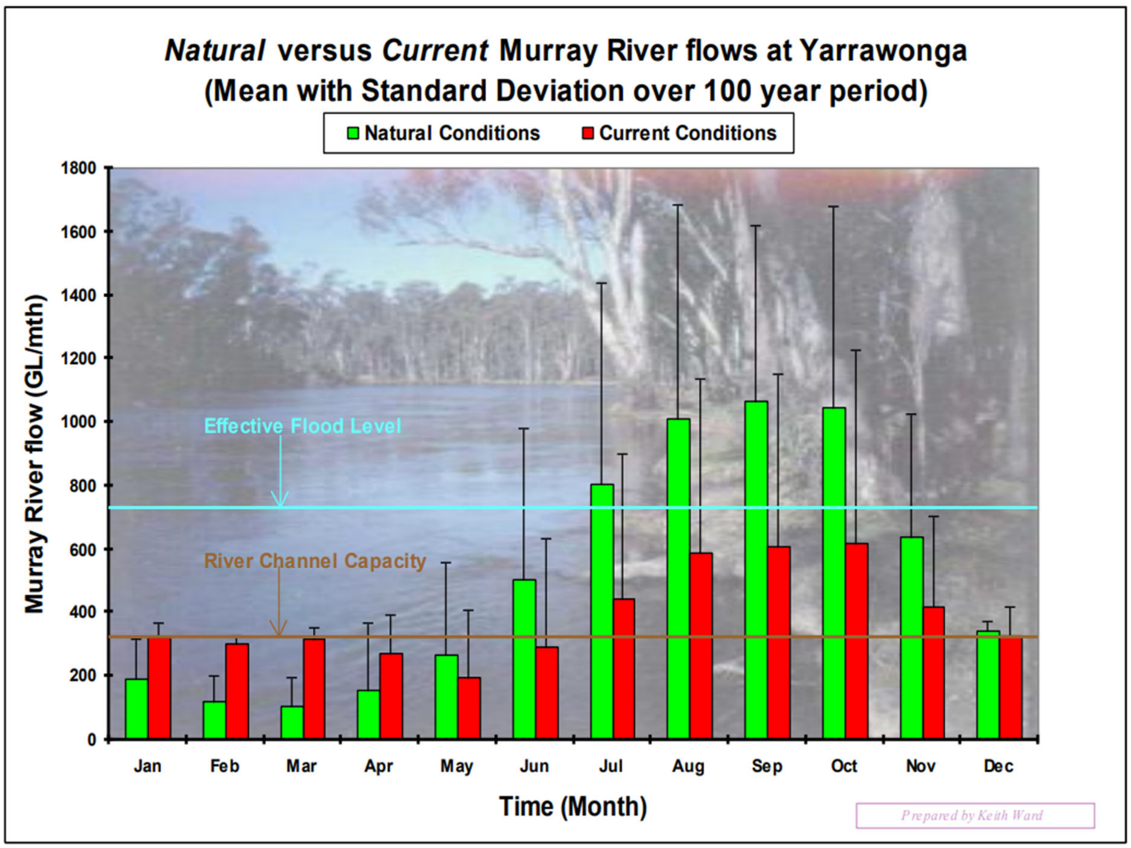

Figure 6-9. *Natural flows compared against current conditions for monthly releases downstream of Yarrawonga Weir (GB CMA 2013).*

Gower *et al.* (2020) modelled the effect of regulation on transport of bedload through the Choke. They found that although flooding did occur regulation reduced the peak of the floods. The result on bed sediment transport of lower flood peaks and long duration high stage regulated flows was that it was reduced overall. This was the result of a larger reduction of sand transport during floods than the smaller increase in transport of sands during long duration regulated flows.

Another consequence of longer duration regulated flows can be the increase in supply from erosion of riverbanks. Regulation tends to hold relatively stable flows in the channel, these would not occur under natural conditions. An analysis of the regulated flows through the Choke from 1985 to 2019 (HARC 2020) indicates that the frequency of near or above capacity flows during January to April has in general not increased during this time.

Water Technology (2020) observed that bank face and in-channel vegetation in their study reach was notably absent, apart from isolated zones where macrophytes have established (**Figure 6-10**). MDBA (2017) report rates of erosion due to boat wash near Corowa as averaging 7.6 mm per day. If these rates were experienced between Yarrawonga Weir and Picnic Point we would expect to see bank widening outside of the range of error of LiDAR Digital Terrain Models (DTM) of Difference (DoDs) (usually +/- 0.2 m for each run, resulting in a total error of +/- 0.4 m) over the 16 years analysed between 2001 and 2017 by Water Technology (2020). However, this does not appear to be the case and if erosion had occurred it was at much lower rate.

***Figure 6-10**. Vertical bank faces that Water Technology (2020) consider typical of boat wash induced erosion. The notch halfway up the bank is at the elevation of a regulated release of 9,000 ML/d from Yarrawonga Weir in the summer (Photo from Water Technology 2020).*

Erosion in the channel may not only be of the riverbanks but also the point bars. The analysis in this study (**Appendix A3**) found that there was 27 % decrease in the area of bare sand surfaces on the bars between the 1940s-1950s and 2019, but this appeared to mainly be the result of an increase in vegetation on the bars. The vegetation increase may be due to several causes such as stock exclusion or different climate conditions, but also as a result of lower flood flows and fixed high irrigation stages. It is likely that the result are more stable channel features, however, if we assume the loss in area was erosion then this could have produced 1.4 million m^3 of coarse sand within the reach since impoundment upstream.

6.7 Changes in the sources of bed sediment from regulation

The major change in the source of bed sediment would have been the building of Hume Dam wall (1934) and Yarrawonga Weir (1939). It is suggested that both structures block nearly all the downstream transport of course bed sediment, resulting in no bed sediment supply out of Yarrawonga Weir. This would mean that any bed sediment entering the River Murray in Reaches 1 and 2 since 1939 would have come from within the reaches.

Riverbank erosion within the reach from 1876-2015 only accounts for 11 % of the coarse sand in the bed. Therefore, even if all the erosion were considered to have resulted from regulation, it does not explain the source of 89 % of the coarse sand.

6.8 Changes in the processes that affect bedload transport rates from regulation

Regulation of flows out of Lake Mulwala has slightly decreased the magnitude of large floods, however, inchannel flows are maintained at fixed high stages for longer than pre-regulation. An analysis of the regulated flows through the Choke from 1985 to 2019 suggests the frequency of near or above capacity flows during January to April has in general not increased. Bed levels at the Tocumwal gauge suggest that the majority of change in bed level has occurred after flood events. Analysis by Gower *et al.* (2020) shows that regulation has resulted in a net reduction of bedload transport. This was due to the larger reduction of sand transport during floods relative to a smaller increase in transport of sand associated with irrigation flows of long duration. However, it should be noted that flood years have higher bedload transport rates than non-flood years.

The regulation of effluents means that the loss of flow downstream has altered from pre-regulation conditions. This could slightly alter the distribution of sediment deposition within the Choke, potentially moving the bedload further downstream than under natural conditions.

6.9 Conclusions

It has been assumed that since 1939 there has no longer been any bed sediment entering the River Murray from above Yarrawonga Weir. This has been based around estimates of sediment trapping capacity for each of the impoundments. The strength of this conclusion would increase based on more data on rates and sizes of sediment on the storage lake beds to confirm that all sand or gravels have dropped out upstream in the impoundments. It has also been assumed that local sources within Reaches 1 and 2 such as overland flow and small tributaries would not have the transport capacity to mobilize significant volume of coarse sand.

If, regulation was responsible for most of the channel widening reported by Gippel and Lucas (2002) and Rutherfurd and Kenyon (2005) then there would have been a change in the sediment budget of the reach switching from upstream supply pre-regulation to internal sources after impoundment. However, the riverbank erosion from Yarrawonga Weir to Picnic Point was not sufficient to explain the >20 million m^3 of coarse sand in the bed of the reach even if potential erosion from point bars was also included.

The ability of the channel to convey both flow and sediment has changed because of regulation. Artificial levees have been built and effluents have been blocked by regulators. This may mean that bed sediment can be transported further down the reach towards Picnic Point before the sand aggrades on the bed into longer term storage reducing channel capacity. However, overall, the rates of bedload transport through the Choke have decreased as a result in the reduction of flood peaks. This means that although there may be riverbank erosion as a result of long duration in-channel flows the ability to transport any coarse sand out of the reach has reduced.

Table 6-3. Summary Box 5

- Both Lake Hume (since 1934) and Lake Mulwala (since 1939) trap all sand entering into them, stopping the contribution of sand to the Choke from riverbed transport at Yarrawonga Weir.
- The rate of aggradation in Lakes Hume and Mulwala appear to be low, indicating that not much bed sediment has moved into the impoundments since they became operational. This would suggest that if a pulse of sediment were moving downstream to Picnic Point it would have had to have been in Reaches 1 and 2 completely before 1939.
- Bed sediment supply for Picnic Point since 1939 must have come from within Reaches 1 and 2. This means either it was there already, or it came from bank erosion within the reach. Other local sources were unlikely to have produced significant volumes of coarse sand.
- The levees and regulator operations from Yarrawonga Weir to Picnic Point suggest that both flows and bed sediment have been more efficiently delivered to the Choke, with fewer losses to the floodplain and effluents.
- There has been channel enlargement and bed armouring near to Yarrawonga Weir which is indicative of clearwater scour downstream of a reservoir and may also be the result long periods of high in channel regulated flows.
- Rates of bedload transport through the Choke have decreased as a result in the reduction of flood peaks.
- Even if all 2.3 million m^3 of coarse sand from bank erosion between 1876-2015 were ascribed to regulation around 90% of the coarse sand on the bed must have come from another source.
- If regulation were responsible for the change in area bare sand surface on point bars, then this could have produced 1.4 million m^3 of the coarse sand in the bed. In combination with bank erosion this means that this only explains <20 % of the coarse sand in Reaches 1 and 2, >80 % must have come from another source.

7 Did land-use change, including historical gold mining, supply the coarse sand bedload?

7.1 Hypothesis

There have been several land-use changes that may have changed the sediment budget of the River Murray catchment (**Table 2-1**). Aggradation in the reach may be because of the migration of a sediment pulse (also termed sediment slug) downstream before the construction of Yarrawonga Weir blocked further transport of bed sediment downstream. The implications of this are that the increased rates of sand input may have occurred historically and, although they are now causing problems downstream, the source may have reduced. This would shift the emphasis of any management from controlling sources of sediment to reducing the impact of the sediment currently in the system. Two major historic land-use changes will be considered as potentially large sources of bed sediment: (1) hillslope, gully and riverbank erosion caused by vegetation and land management alterations from reference conditions modelled using SedNet, and (2) inputs from historic gold mining.

7.2 Pre- and post-European settlement yields

Land-clearance across Australia has changed the sediment budgets of rivers. The main alterations come from:

1. Land clearance reducing surface roughness and increasing overland flow velocities, resulting in increased hillslope erosion.
2. Vegetation clearance reducing evapotranspiration and increasing surface runoff, resulting in higher discharges.
3. Higher stream discharges combined with vegetation clearance along streams causing increased bank erosion.
4. Regulation has stopped the connectivity of sediment through the river system.

In the National Land and Water Resources Audit (NLWRA) the SedNet model was used to estimate changes to the sediment budgets of rivers across Australia from pre-European conditions to a current situation (NLWRA 2001). In SedNet the hillslopes were assumed to contribute sediment that was mainly fine textured, contributing to the suspended sediment loads. Gullies and riverbanks were modelled as contributing 60 % of their eroded volume as coarser particles which would end up as bedload.

SedNet appeared to poorly predict bedload accumulation when regional models were compared against whole of MDB models (CSIRO 2003). Despite this, the modelled data provides a consistent estimate of sediment loads that can be used for comparison and an indication of where particular geomorphic issues may occur.

The data in **Table 7-1** show the SedNet results for the catchments upstream of Picnic Point based on data from NLWRA (2001). Data from historic gold mining has also been included for comparison and will be discussed later in this this section. Overall, the contributing basins of the Upper Murray, Kiewa and Ovens, along with part of the Murray-Riverina (**Figure 3-1**) have sediment loads that are between 3 and 103 times the pre-European modelled loads (**Table 7-1**).

The largest contributing catchment is the Upper Murray River, with an area of 15,338 km^2. A sediment supply of 0.45 t/ha/yr was predicted for this basin. Compared to the other contributing basins the proportion of agricultural land is low, with only 8 % of the land area being agricultural. The proportion of sediment supplied from bank erosion and gullies was 45 % and 31 % respectively. The overall predicted supply to rivers was around 727,000 t/yr.

The Kiewa is a small narrow relatively steep basin with an area of 1,916 km^2. Improved pasture makes up almost all the total agricultural land that constitutes 14 % of the basin. Bank erosion was predicted to supply 62 % of the sediment supplied to rivers. The small basin produces less sediment overall, around 108,000 t/yr, however, it has a relatively high supply per unit area of 0.56 t/ha/yr.

The Ovens River basin area of 7,986 km^2 is around half that of the Upper Murray River. Improved pasture, again, makes up most of the agricultural land use with 18 % of the basin being agricultural land. Bank erosion was predicted to have supplied half of the 422,000 t/yr of sediment contributed to rivers, with gullies supplying 40 %. The sediment supply increase of 24 times post-European settlement was a much higher increase than the Upper Murray (8 x) and Kiewa (3 x).

Whilst the Murray-Riverina Basin has a catchment area similar to the Upper Murray River only around 2,400 km^2, 16 % of the Basin, are upstream of Picnic Point. The Murray-Riverina has the largest increase in the amount of sediment contributed to rivers after European settlement. The increase in supply of 103 times was almost all contributed from riverbank erosion.

Whilst detailed spatial data from the CSIRO modelled runs was not available, **Figure 7-1** suggests low bed sediment rates in the regulated reach. The exception is near to the Barmah township where there was a small area of >1 m deposition.

Table 7-1. *Modelled sediment contribution to rivers in the sub-catchments that are upstream or contain the Barmah Choke (NLWRA 2001). The gold-coloured part of the table are estimates of sediment contributed from historic gold mining based on estimates from Davies et al. (2018).*

Basin number	**401**	**402**	**403**	**409**
Basin name	Upper Murray River	Kiewa	Ovens	Murray-Riverina
Basin area (km²)	15,338	1,916	7,986	15,055
Improved pasture (%)	7.6	13.87	13.85	11.13
Cropping (%)	0.67	0	3.26	17.34
Horticulture (%)	0.11	0.4	1.01	1.67
Total agricultural land proportion (%)	8.39	14.26	18.12	30.14
Rain (mm/yr)	1,119	1,232	1,027	399
Total evaporation (mm/yr)	615	622	569	398
Runoff (mm/yr)	505	612	463	59
Sediment supplied to rivers (t/yr)	726,767	107,968	422,132	1,094,539
Sediment supply (t/ha/yr)	0.45	0.56	0.52	1.04
Proportion from hillslopes (%)	22.93	13.23	9.66	1.49
Proportion from bank erosion (%)	45.49	61.84	50.26	88.05
Proportion from gullies (%)	31.58	24.93	40.07	10.46
Proportion of length with bed deposition > 0.3 m (proportion)	0.03	0	0.09	0.25
Sed Ratio (Euro:pre-Euro) (ratio)	8	3	24	103
Sediment export to the coast (t/yr)	2,783	4,582	15,788	101,001
Specific sediment export to the coast (t/ha/yr)	0	0.02	0.02	0.1
River sediment delivery ratio (export/supply to streams) (ratio)	0	0.04	0.04	0.09
Pre-European sediment supplied to rivers (t/yr)	90,846	35,989	17,589	10,627
Estimated gold mine tailings supplied to rivers 1859-1891 (t/yr)	4,822,000	1,080,000	4,504,000	2,392,000
Ratio of gold ore (sludge) to background yield (ratio)	53	30	256	225
Ratio of gold ore (sludge) to post-European settlement yield (ratio)	6.6	6.3	10.7	2.2

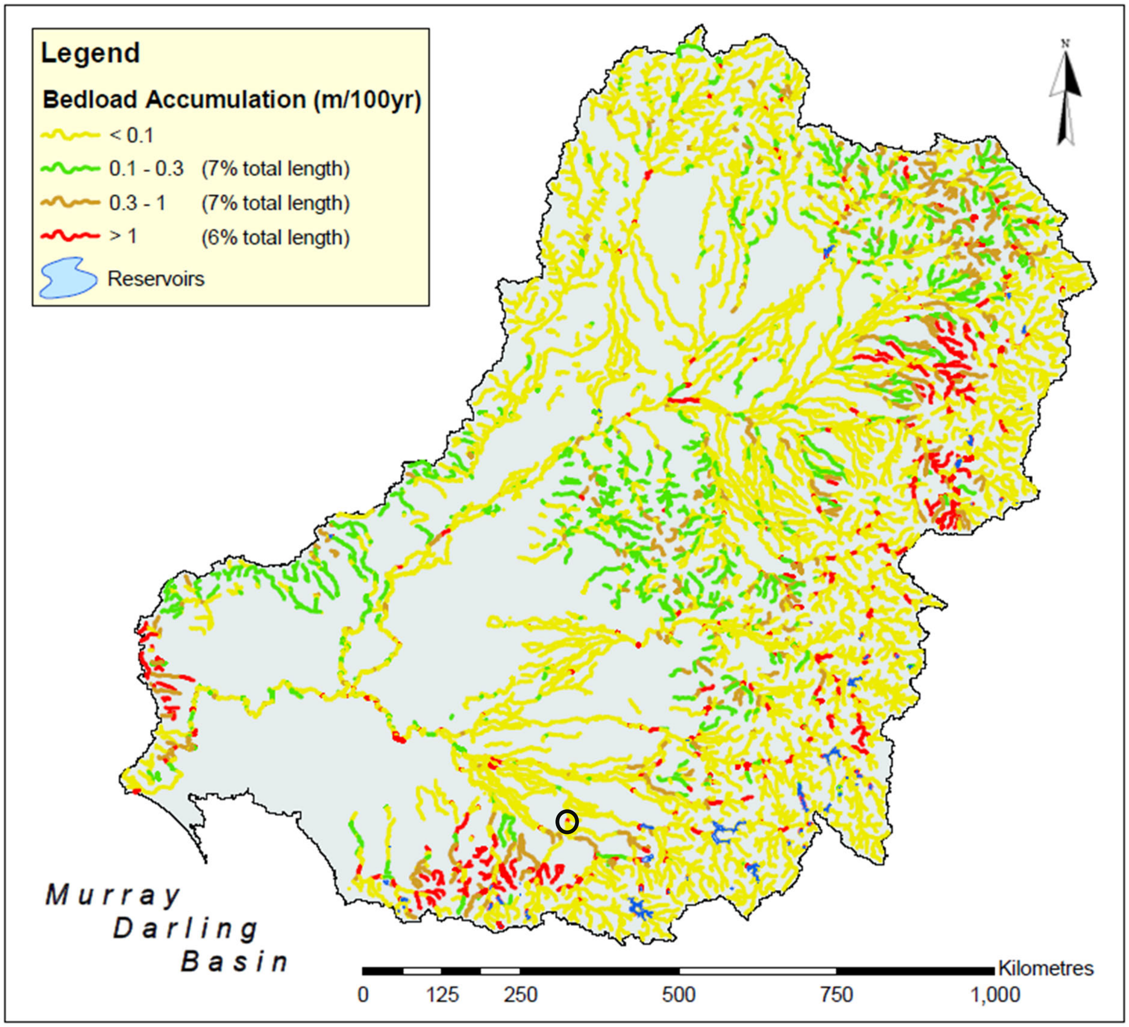

Figure 7-1. *Predicted bedload accumulation based on SedNet data for the Murray Darling Basin (CSIRO 2003 p12). The township of Barmah is circled in black.*

7.3 Gold mining sediment production

The sediment modelling in SedNet does not overtly include changes because of historic mining activities although some of the land clearance may have been associated with them. A recent Australian Research Council (ARC) project 'Rivers of Gold' has used historical records to estimate the mobilization of sediment by historic gold mining into Victorian rivers (Davies *et al.* 2018). The concentration on Victoria was because of the existing data sources but there was also significant mining in the parts of the Murray-Darling Basin in NSW (**Figure 7-2**).

Gold mines were in places where either gold had been placed geologically (primary mines) or eroded and redeposited (placer mines). Mines were often in upstream catchments, on average in sub-catchments with an area of around 70 km^2 and 10 km from the headwaters (**Figure 7-3**). In the catchments upstream of Picnic Point the main Victorian streams that had gold mines were the Ovens River and Mitta Mitta River.

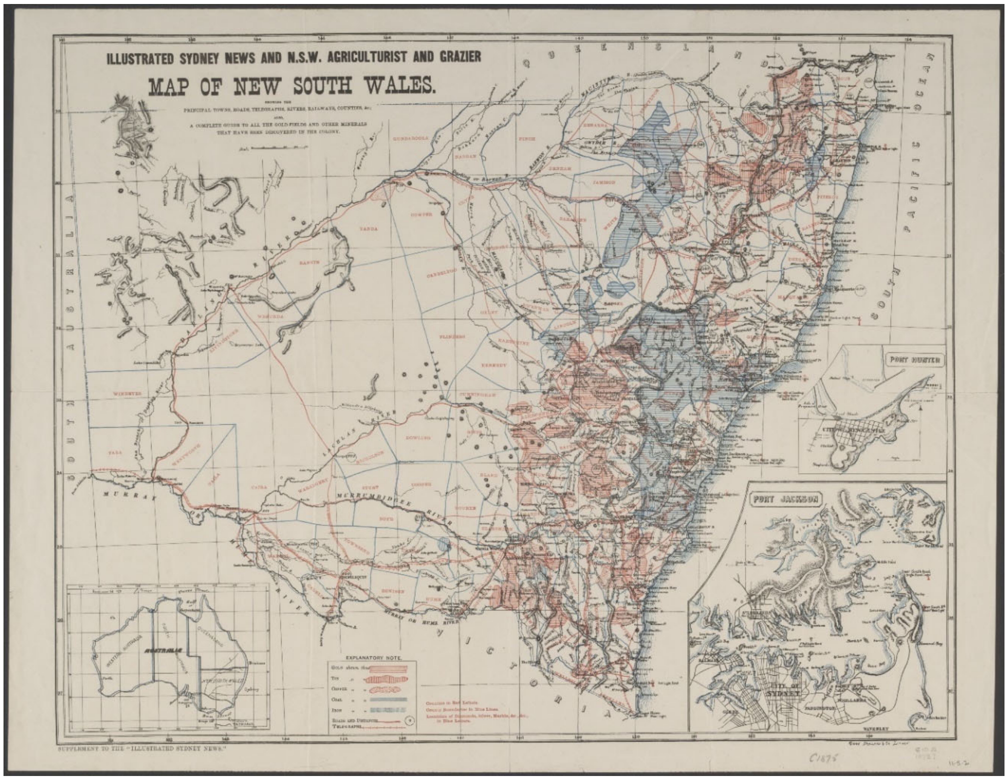

Figure 7-2. *A map of New South Wales showing the principal towns, roads, telegraphs, rivers, railways, counties & also a complete guide to all the goldfields and other minerals that have been discovered in the colony (Gibbs 1872).*

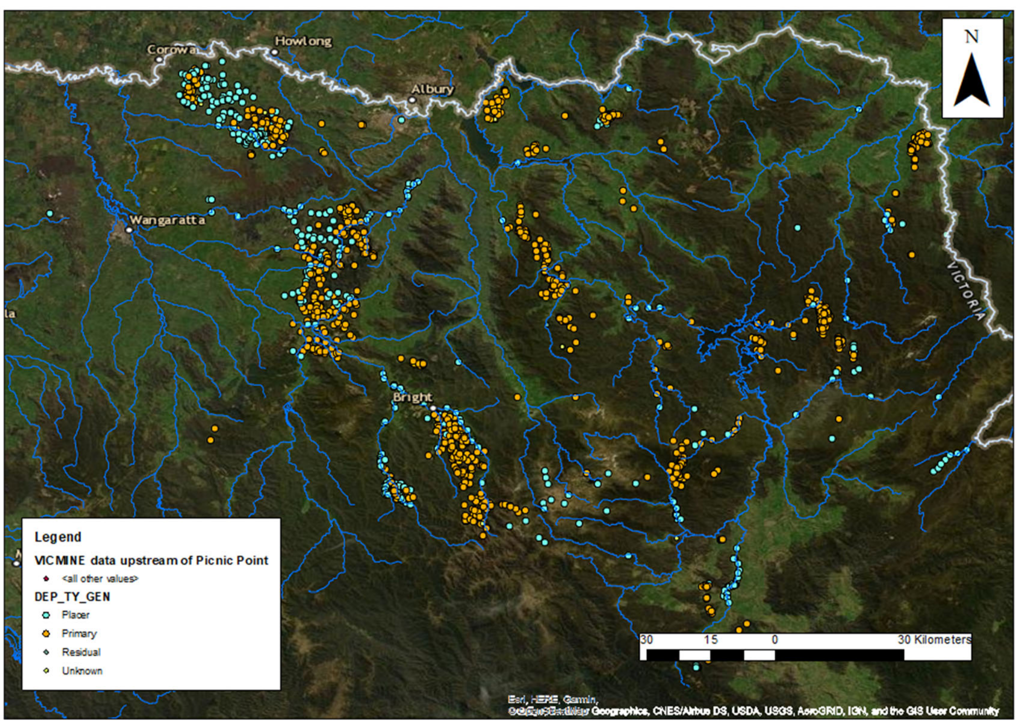

Figure 7-3. *VICMINE data showing the distribution of placer and primary mines with known locations upstream of Picnic Point and in Victoria .*

Grove *et al.* (2019) divided the progression and quantification of mining into the following stages:

1. Pre-European settlement (pre-1803)
2. Pre-mining (1803 – 1851)
3. Gold rushes (1851 – 1880)
4. High volume mining (1880 – 1905)
5. Environmental regulation (1905 – 1950)
6. Dredging (1899 – 1950)
7. Incision and downstream redistribution (non-dredged sites approximately 1890s, dredged sites approximately 1930s – 80s).

River channels may have not been in an unaltered or pristine state before gold mining commenced, with land clearance having already occurred (Stages 1 and 2). However, the high number of migrants in the gold rushes led to both land clearance and sediment mobilization into rivers. The detailed quantification of sediment yields into the river systems is based on quarterly reports from the District Mining Surveyors and Registrars covering the period from 1859 to 1891 (Davies *et al.* 2018).

The Beechworth mining district, which is the main source of sediment for the Barmah reach, can be seen to have produced the highest sediment yield compared to other mining districts in Victoria (**Figure 7-4**). The main type of mining contributing this sediment was the sluice box, whilst hydraulic sluicing was the second largest.

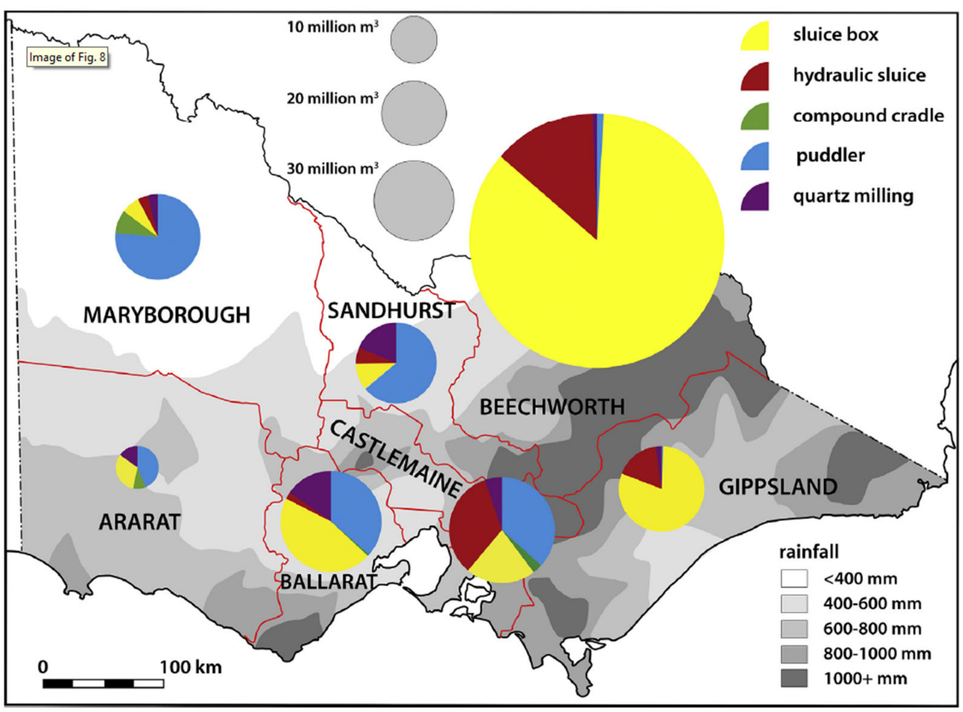

Figure 7-4. *The volumes and types of gold mining that mobilized sediment into Victorian rivers between 1859 and 1891 (Davies et al. 2018).*

Sluice boxes were wooden structures placed in the stream (**Figure 7-5**). The mined sediment was placed at the top of the sluice and water was washed down the box sorting the sediment as it went. Riffles or matting were sometimes placed in the bed of the box to catch the heavier gold. The unwanted sediment was washed downstream. The quantity of water and river slopes in the N.E. of Victoria were conducive to using this technology.

Figure 7-5. *Three men using a long tom and sluice box, ca. 1890 H2009.100/148 (photo courtesy of the State Library of Victoria).*

The number of miners (**Figure 7-6**) operating this relatively small-scale processing system was so large that it the provided an enormous sediment supply directly into the stream (**Figure 7-7**). Coarse sediment, such as cobbles and boulders were removed from the sediment and stacked locally. These stacks were often within the flood extent area and could be moved during high flow events. The sediment processed in the boxes was a range of sizes and so would enter the river as bed, suspended and wash loads.

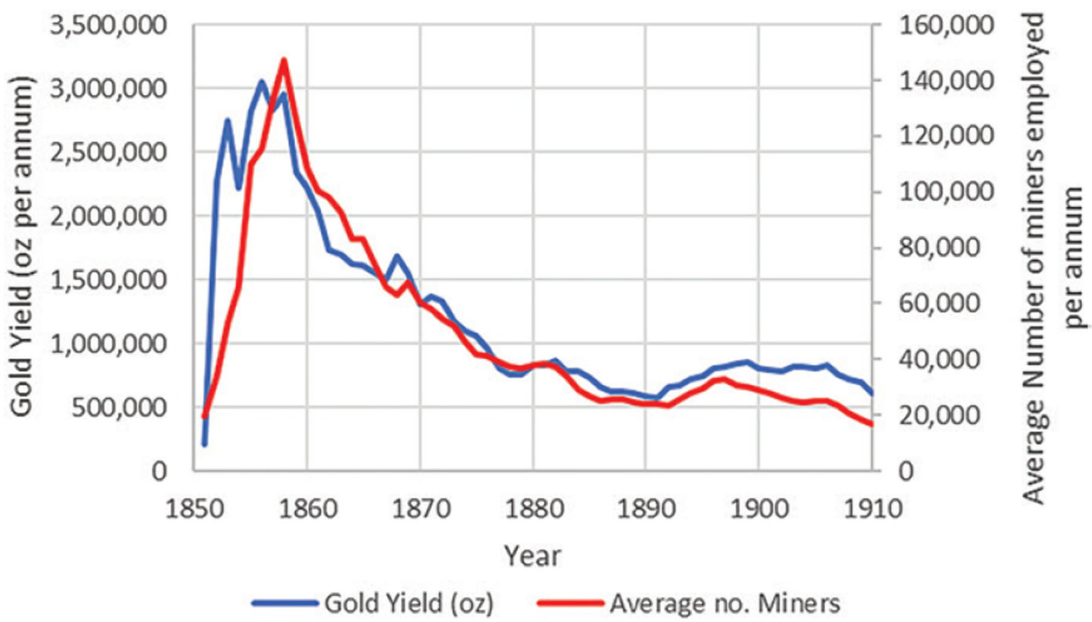

Figure 7-6. *The annual gold yield and average number of employed miners across Victoria between 1850 and 1910 adapted from Dept. of Mines (1910 p.16).*

Figure 7-7. *Mining for gold in the bed of a river in the vicinity of Beechworth, unknown date (courtesy of the State Library of Victoria).*

Hydraulic mining rapidly mobilized huge quantities of sediment to be processed for gold. The technology did not arrive until around the 1880s and so was in Stage 4: high volume mining. A store of water was pumped to a giant monitor (nozzle) and this was jetted at the base of a hillslope. The removal of the base by jetting resulted in wholescale collapse of the face (**Figure 7-8**). Again, this method of mining produced a range of sediment sizes directly into the stream.

These techniques are known as placer mining where the gold has been moved from its original position, usually by the erosion of the geological unit by a river. The other form of mining was primary, where the original geological formation that contained the gold is excavated. Often primary mining involves shafts into the ground the extract the gold under the surface. The rock is removed and brought to the surface and was then crushed to make it easier to extract the gold. Crushing took place in stamp batteries (**Figure 7-9**). These crushed the sediment into a consistent sand size for further processing. The sediment from stamp batteries could be stacked locally or settled out in ponds. The sediment stores were often liberated into rivers during floods. Alternatively, the crushed sediment may have been processed in sluice boxes and the sands directly delivered into the river channel.

Figure 7-8. *Hydraulic sluicing on the Mitta Mitta (courtesy of the State Library of Victoria).*

Figure 7-9. Looking across earth works with miners using a gold washing cradle in the foreground, man standing beside horse-drawn whim and crushing battery with conveyor in background. Photograph taken between 1854 and 1862 (courtesy of the State Library of Victoria).

The sediment yields for the basins that could potentially supply sediment to Picnic Point have been estimated above (**Table 7-1**). The Ovens basin has the biggest difference between both pre- and post-European SedNet results. Mining is conservatively estimated to have mobilized over ten times the sediment from clearance alone. The Upper Murray and Kiewa basins have over six times the SedNet modelled yields.

The sediment sizes mobilized from gold mining vary from fine silts and clays to much larger boulder sizes. The sluice box and hydraulic sluicing that predominated in the Beechworth District (**Figure 7-4**) would have had the large size factions stacked locally to the area mined with predominantly sand and finer grainsizes delivered directly into the stream. Primary mining that involved crushing rock to sand size grains would have contributed a high proportion of sand directly into the rivers.

The estimated Victorian yields from gold mining between 1859 and 1891 were spatially joined with data from the BOM Geofabric (BOM 2020) to estimate the travel distance needed to reach Picnic Point (**Figure 7-10**). The steep slope of the blue line between 200 and 390 km upstream suggests that there was the greater potential supply than further upstream. This would suggest that the greatest volumes of sediment would reach the Murray River first and then there be a gradual tailing off of supply after that. Yarrawonga Weir is 169 km upstream of Picnic Point, and so there is a relatively short travel distance for sediment to reach this position on the Murray. However, it must be remembered that the sediment has been supplied over decades and not simultaneously, and there may be losses out of the system such as onto the floodplain. These types of losses are modelled by SedNet but not by Davies *et al.* (2018).

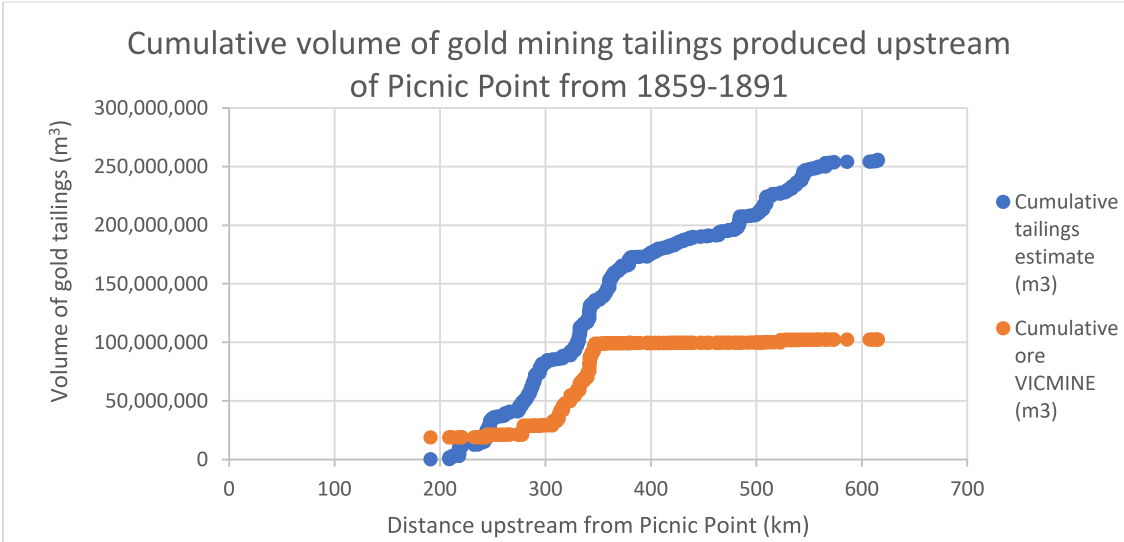

Figure 7-10. *The estimated Victorian gold mining sediment (Davies* et al. *2018) mobilized into rivers upstream of Picnic Point, accumulated in the upstream direction. This is compared against VICMINE data (DPI 2002) that has reported sediment yields, but with many data gaps.*

When mining ceased and the supply of sediment declined the response was incision. Higher, flashier discharges as the result of land clearance and the modification of drainage would have increased the likelihood of incision. This is Stage 7 from Grove *et al.* (2019). In some cases, the channel may have started to incise and then dredging commenced in Victoria, around 1900. The bucket dredges initially worked both in-stream and on the floodplain. Environmental legislation in 1905 moved dredges out of the channel and they worked mainly on floodplains (**Figure 7-11**).

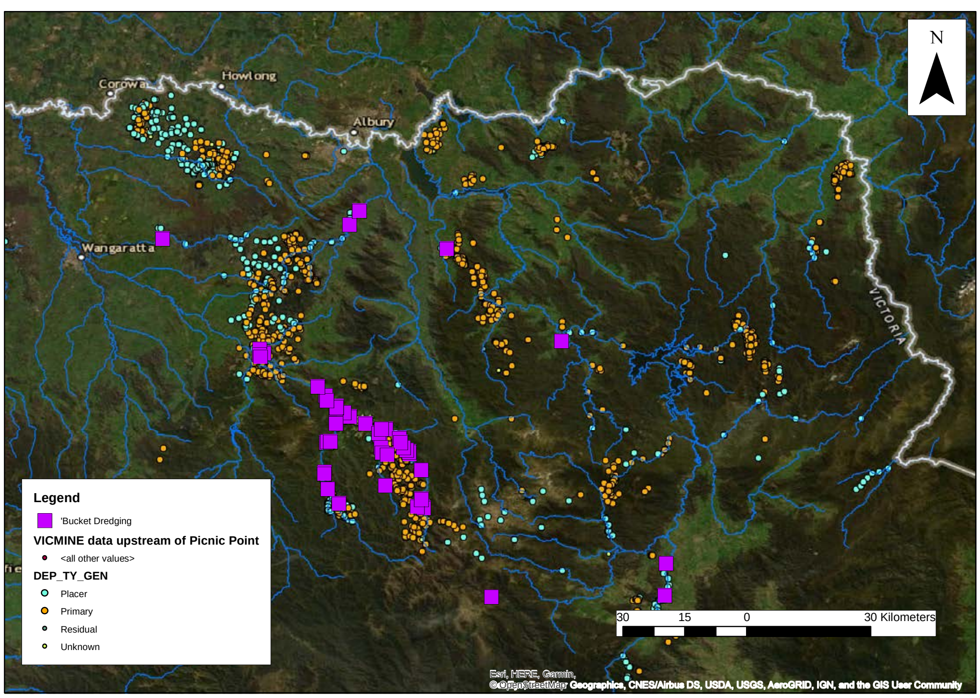

Figure 7-11. The position of spatially located bucket dredges that mined in Victoria upstream of Picnic Point.

Dredging was the last phase of alluvial gold mining. Our understanding of the sediment contribution to the channel from dredging is poor. We have good records of the volume of sediment that was mobilised at the dredge site (around 100 million m^3) but not what may have entered the river. The dredges were large floating factories (**Figure 7-12**). When they were on the floodplain a large hole was dug and filled with water for the dredge to sit in. Buckets on the front of the dredge dug down into the sediment, up to 40 m. The sediment was processed onboard and the fine and coarse sediment were transported out of the back to fill up the pit behind. In this process the dredges slowly crept across the floodplain (**Figure 7-13**).

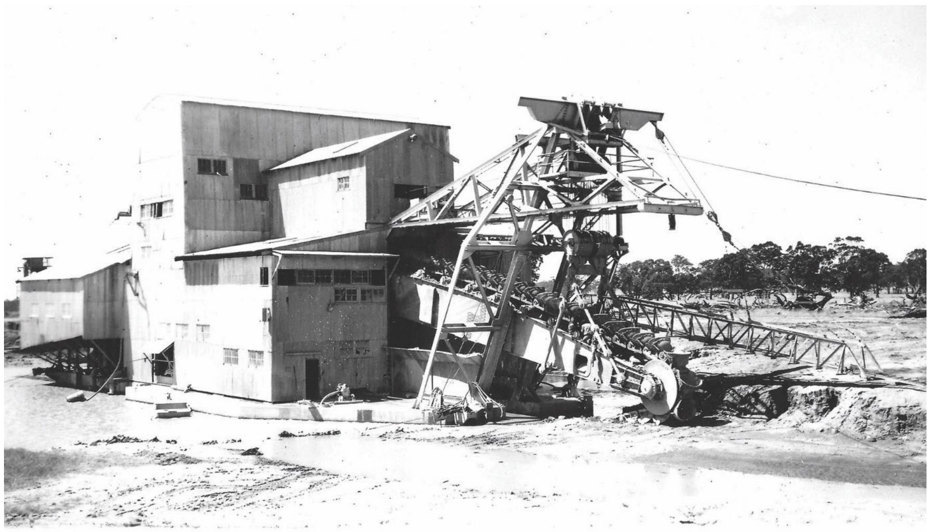

Figure 7-12. *A photograph of the Newstead Dredge on the Loddon River floodplain showing the buckets at the front of the machine.*

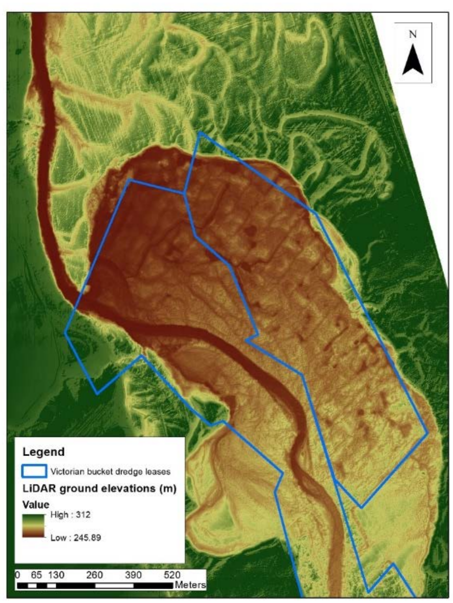

Figure 7-13. *A LiDAR image of the dredge area of the Ovens floodplain showing the absences of palaeochannels and the linear tracts made by the dredge moving perpendicular to the channel.*

"At present whenever dredging is carried on the streams are contaminated, not only in the dredging district, but along, the whole course of the river or stream, and any larger streams entered, the muddy waters must of necessity foul them also.

Take the Ovens River, for example, it is at present carrying along in its waters all the sediment from the upper reaches about Bright and depositing it at the various bends and turns all the way down. At Wangaratta the bed of the stream is being rapidly silted up, and places where once there were deep holes are now banks of sand stretching all along the course. The water, too, is in a filthy state, and must continue so until it reaches, the Murray. What must that river be like now with the- dredging of late years and its results? The way things are it cannot be very long before all our streams will carry yellow fluid in place of the once clearwater." (The Bendigo Independent 1909 p.1)

Anecdotal evidence suggests that subsequent redeposition may have occurred in channels that had started to incise, and once the dredging ended the channels would have started to re-incise. This could have been as recently as 1955 for the Tronoh dredge in Harrietville on the Ovens River. An example of incision after a pulse of sand sized sediment downstream of dredge site can be seen at Eldorado, Victoria (**Figure 7-14**) The dredge operated from 1936 to 1954 and has resulted in high loads of sand sized sediment both in the channel and on the floodplain of Reedy Creek. The sand pulse is now migrating downstream towards the Ovens River.

Figure 7-14. *A 2010 aerial photograph of the Reedy Creek, a tributary of the Ovens River. The Eldorado dredge is floating in a dredge pond in the top right of the image. Flow is from right to left of the figure.*

7.1 The combined impact of land clearance and gold mining on sediment in the River Murray

Both gold mined sediment and sediment from land clearance may have been mobilized simultaneously. The result was a rapid increase in sediment loads to streams, many of which were in the upstream reaches of the basins and may have been discontinuous with on-line wetlands. These channels filled with sediment and subsequent sediment then ended up on the floodplain. The floodplains aggraded, in some cases by as much as 2 m.

"Rede's Creek is so much filled that, in the property of Mr. Charlton, about four miles above Wangaratta, the old watercourse is completely obliterated by the deposit of sludge, and a new channel has been formed. The deposit reaches to the top of the old boundary fence on the property, and a further deposit occurs with every heavy rain." (Sludge Committee 1887 p. xxv)

"*5456. What do you regard as the cause of the pollution of which you speak ?*

The sluicing works on both sides of the Murray. I had occasion, about April last, to be in Tumbarumba, and I saw there the sluicing operations just above the town and also on Burra Creek. I saw the water as it passes down near Tooma, and it was just like liquid mud rolling down—quite red. On the other side, in company with the Mayor and others, I visited the channel that runs into the Mitta River, above Huon's Lane. There is a channel cut there to take the water from the mine—that is, the overflow from these mining operations—back to the Mitta, and they have cut a channel so as to save the sludge going over people's paddocks. This channel was just rolling mud. As we drew up in our trap the men working on the road cried out, "Do not drink it; it is not fit to drink." The Mayor took a fair sample (produced) from the running stream that goes straight into the Mitta River. After getting that specimen we went round to Bethanga Creek, which also runs into the Mitta, and the water there was almost the colour of blood and full of minerals (specimen produced)." (Interstate Royal Commission on River Murray 1902 p.220)

It is likely that a substantial amount of the mined sediment ended up being stored on the floodplains downstream of mined sites, especially once they went from being confined by hillslopes to a floodplain. The ability to process mined sediment in the channel was hampered by the channel filling with sediment. This, and regulations to stop the sediment mined upstream impacting miners downstream, resulted in sludge channels being built to convey sediment downstream more efficiently. Whilst it is unlikely the sediment would all have been transported in these channels directly into the River Murray, they did supply sediment at the lower end of the Ovens and Mitta Mitta meaning that there were short travel distances for that sediment to reach the River Murray.

When mining ceased, the incision of infilled channels created a secondary pulse of mining sediment downstream, this would be mixed with sediment supplied from land clearance that would also have been part of the infill in the channel and deposited on the floodplain. As channel incision progressed it would eventually have eroded into the pre-European bed and floodplain sediment. The channel incision would have meant that the floodplain became less and less well connected. This means the sediment eroded in the channel may have reached the River Murray more efficiently once mining ceased from the 1890s to the 1980s.

There were complaints about sludge in the River Murray reported in Corowa (The Corowa Chronicle 1907) when a meeting was held with the Victorian Minister of Mines. This could indicate the timing of a sediment pulse reaching this point of the River Murray. Discussions made around the filling of waterholes on the Murray and Ovens Rivers. Waterholes were suggested to have filled in a fifteen-year period (assumed to be 1892 -1907) by up to 3 m, going from 20 ft (6 m) to 10 ft (3 m) deep. However, the grainsize of the sediment filling the holes was not reported

During the same period as the waterholes were filling the condition of the River Murray at Yarrawonga was said to be '*so bad it could no longer be ignored*'. The Murray River between Albury and Echuca was likened to a '*stream of pea soup*' because of the load of sediment attributed to mining sludge. This colouration is more likely because of high suspended loads of silts and clays. Complaints were made about input of sludge Yackandandah Creek in Victoria and from Tumbarumba Creek in NSW. The latter is a tributary of Tooma Creek that enters the River Murray near to Tintaldra. The minister whilst sympathetic to issue of pollution from sludge was quick to point out that there had been substantial '*groundless accusations*' made, and that '*natural*' erosion of rivers had also been ignored.

It is difficult to trace the source of the sediment from land clearance, Gingele and De Deckker (2005) did some sediment fingerprinting in the MDB but this was mainly concentrated on the suspended load. The mining sediment is often high in heavy metal concentrations. Samples taken in the ARC Rivers of Gold project on incised channel riverbanks had elevated concentrations of Arsenic (As) above the contact with the pre-aggradation floodplain. This suggested that it may be a useful tracer of the presence of mining sediment if sufficiently elevated above backgrounds concentrations (Grove *et al.* 2019). However, heavy metal concentrations are often higher in finer grainsizes. The coarse sands in the riverbed are unlikely to have high metal concentrations, and preliminary sampling has indicated that the heavy metal concentrations are below Victorian and NSW Environmental Protection Agency guideline values (Maher 2021).

Thoms (2007) sampled surface bed sediment in the lower River Murray between Locks 2 and 4 (**Figure 7-15**). The elevated heavy metal concentrations at the Locks were suggested to be indicative of urbanisation. It is possible they could have come from sludge in River Murray that had passed through the Choke, mined sediment could also have come from tributaries downstream of the Choke such as the Loddon River in Victoria (Abernethy *et al.* 2004). Samples were also taken on the Barmah-Millewa Forest floodplain (**Figure 7-16**). These also show elevated heavy metal concentrations, and these appear to have increased since the Cs^{137} detection level in the cores that indicates a date of 1954. These heavy metal concentrations were again thought to be associated with the growth of urban centres.

Land clearance and gold mining would have resulted in high loads of bed sediment being mobilized into the channel for over 170 years. The proportion of this sediment that was sand sized is difficult to determine.

If the heavy metal concentrations found by Thoms (1995) can be ascribed to gold mining, then it would suggest that there has been deposition from that sediment source in the Barmah Forest, and this includes sand sized deposits (**Figure 7-16**). This would concur with the heavy metals found by Baldwin *et al.* (2008). However, there is limited evidence from surface samples in Lake Mulwala to indicate high metal concentrations currently being accumulated in the bed.

There has been up to 256 times the modelled sediment yields mobilized into sediment supply area 1 (**Figure 3-1**) because of gold mining. Land clearance and gold mining often occurred at the same time, with a peak in the numbers of miners in the 1860s. It is not known the exact proportion of this supply that was coarse sand sized sediment, and how much of it made it into Reach 1. SedNet (CSIRO 2003) suggests that there was 25 % of the Murray Riverina sub-catchment that had aggradation on the bed of more than 0.3 m. It is likely that there were a series of pulses of sediment into Reach 1 that were long and low in elevation, based around the fact that sandy sediment would be stored and reworked in many cases before it ended up in the River Murray.

This sediment would have been mobilized into Reach 1 before the construction of Hume Dam and Yarrawonga Weir. After this point the sand sized sediment would have been trapped. There appears to be low rates of sand deposition in Lake Mulwala after impoundment, suggesting that if a pulse or pulses of bed sediment had made it into the River Murray it had transited downstream of this point by 1939. Alternatively, the conditions of high bedload supply may have meant that once the supply was reduced a relatively immobile sheet of coarse sand was left behind that extended all the way from Picnic Point into the mined tributaries, such as the Ovens River. Impoundment may have only separated out areas of a long very slow-moving sheet of sediment. This would explain the relatively homogeneous distribution of sediment volumes observed by the SBP in Reach 1 (**Figure 4-3**).

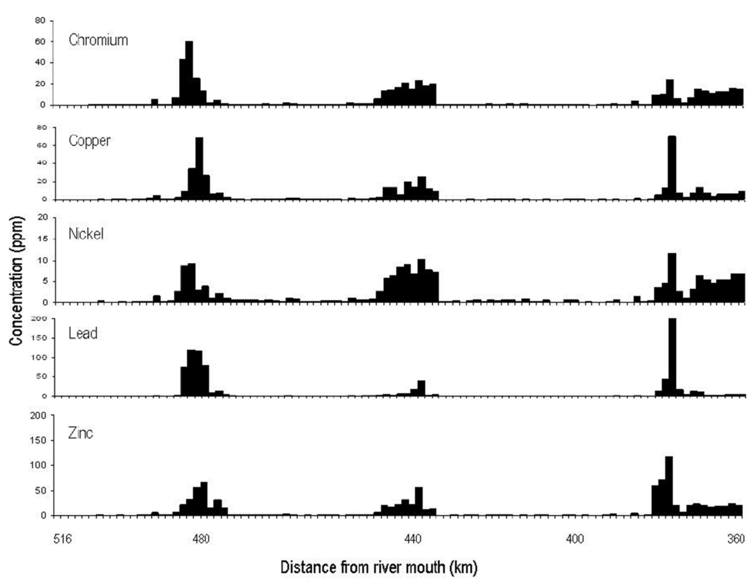

***Figure 7-15**. The sampled concentrations of 100 bed surface sediment samples on the River Murray between Locks 2 and 4 (Thoms 2007 p.151).*

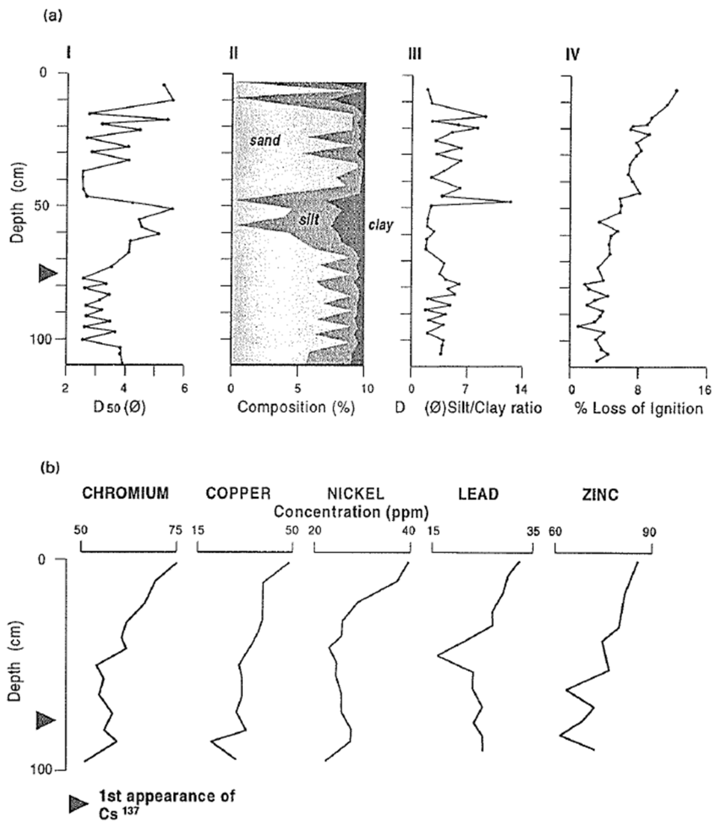

Figure 7-16. *The textural and geochemical character of the sediments in the core extracted from the Barmah Forest: (a) sediment texture; (b) heavy metal concentrations (Thoms 1995 p.125).*

To provide an indicative figure for the potential supply of bedload in Reaches 1 and 2 the same period of 1859-1891 used to estimate volumes of sediment produced by gold mining has also been used for upstream gully and riverbank erosion from land clearance (**Appendix A4**). The resulting coarse sediment volumes were 17 million m^3 from land clearance gully and bank erosion, and 125 million m^3 from gold mining. This is an underestimate of the volumes created as they would be supplied over a longer time period, but they are also an overestimate of what has been mobilized downstream of Yarrawonga Weir as deposition has not been included. These estimates of bedload allow a comparison with the coarse sand in the bed between Yarrawonga Weir and Picnic Point. Gold mining could have produced six times the bedload volume, whilst gullying and bank erosion from upstream land clearance could have produced 85 % of the bedload volume.

7.2 Conclusions

It has been assumed that both Lake Hume and Lake Mulwala trap all bed sediment. These storages have had low rates of sedimentation since construction and so any pulse of sediment from land clearance or gold mining sources above Lake Hume must have made it past the current dam wall location before 1934 and past the current Yarrawonga Weir before 1939. This will include any mining sediment from the Mitta Mitta. Similarly, any sediment pulse between Hume Dam and Yarrawonga Weir, such as sediment supplied by the Ovens River, must have passed through the current position of Yarrawonga Weir by 1939.

It appears a very high coincidence that Yarrawonga Weir should have been built as the very time the sediment pulse had passed through that point. The depth of mobile bed sediment remains high throughout Reaches 1 and 2 (**Figure 1-11**) which is not indicative of a pulse of sediment with an upstream tail as the sediment is evacuated. It is possible that a much greater extent of the Murray has been filled with coarse sand, such as up to the confluence of tributaries with high sediment yields such as the Ovens River. Once the high rates of sediment mobilization halted the emplaced sediments have been transported very slowly and stopped for the extent of Lake Mulwala. In this case the upstream tail of the sediment pulse may lie upstream in the mined tributaries such at the Ovens River.

For the leading edge of the mining pulse there is evidence of heavy metals on the Barmah floodplain along with deposition of fine sand (Thoms 1995), and there is also finer sediment with heavy metal contaminants further downstream on Locks 2 and 4 (Thoms 2007).

It has been estimated that 142 million m^3 of bedload could have been supplied from land clearance gullying and bank erosion combined with the gold mining sediment supply that has been quantified in Victoria. This is around over seven times the volume in the bed from Yarrawonga Weir to Picnic Point and suggests, despite the many assumptions in the calculations, it would be sufficient to supply the estimated >20 million m^3 of coarse sand.

Table 7-2. Summary Box 6

- Both land clearance and gold mining have increased bed sediment into tributaries of the River Murray.
- Modelling by CSIRO (2003) does not indicate high levels of bed aggradation in Reaches 1 and 2 other than just downstream of Yarrawonga Weir, and there are also some raised levels downstream of Picnic Point.
- Mining produced large volumes of sediment that filled channels and then deposited on floodplains. Once gold mining ceased the channel incised and it is this sediment that may have reached the River Murray more efficiently from the 1890s to the 1980s.
- Heavy metals that could have been sourced from historic gold mining sediment have been found in Lake Hume, Lake Mulwala, the Barmah floodplain and in River Murray Locks 2 and 4. This suggests that gold mined suspended sediment has made it to these locations, and it could be that fine sand from gold mining may have made it on to the Barmah floodplain.
- The coarse sands in the riverbed are unlikely to have high metal concentrations, and preliminary sampling has indicated that the heavy metal concentrations are below Victorian and NSW Environmental Protection Agency guideline values (Maher 2021)
- Sediment from land use change may be stored in Reaches 1 and 2, but if it is, it must have passed though Yarrawonga Weir before 1939.
- Estimates of bedload production by gold mining, riverbank erosion and gullying upstream of Yarrawonga Weir indicate there would be sufficient sediment produce the 20 million m^3 of coarse sand in the riverbed.

8 Was desnagging responsible for mobilising and supplying excess bed sediment?

8.1 Hypothesis

The removal of large wood in channels both increases the flow velocity by reducing friction/roughness and decreases the cohesion of the bed. These factors in combination can lead to a higher flux of bed sediment (Erskine and Webb 2003).

There have been several desnagging operations in the River Murray (**Table 2-1**) and these will be investigated to see if they could have introduced the current excess of sediment into the Choke. The earliest efforts will be concentrated on as they are likely to have caused the greatest geomorphic change from reference and provide some information on the pre-snagging reference conditions. Desnagging also occurred in the tributaries of the River Murray upstream of Picnic Point. This potential supply of sediment will also be briefly considered.

8.2 Reference condition

There are descriptions of the early wood loads in the river, but these are mainly anecdotal. One of the main considerations was the pre-European supply of wood to the channel. What did the riparian zone that supplies large wood look like?

Sturt (1844) describes his traverse of the Murray in 1838. They descended the river to the junction of the Ovens River taking the northern or right bank of the Murray.

"About 25 miles below the junction of the Ovens, however, the current in the river became feebler, its waters were turbid, the flats along its banks expanded, and appeared subject to inundation, and detached masses of reeds were scattered over them: these, at length, almost covered the primary levels, and, by the increasing height of the rings upon the trees, we judged that we were pressing into a region subject at times to deep and extensive floods. Accordingly, as we advanced, the reeds closed in upon us, and we moved through them along narrow lanes or openings which the natives had burnt, the reeds forming an arch over our heads, and growing to the height of 18 or 20 feet. Our progress was impeded by hollows, and the flats were intersected by channels for carrying off the back waters from the extremity of the alluvial flats." (Sturt 1844)

These observations suggest a turbid river that was well connected to the floodplain. Riparian vegetation consisted of trees and reeds. The floodplain had a variable topography, probably because of multiple oxbow lakes/billabongs, but also due to effluents and other channels cut on the floodplain.

Aboriginal burning also indicates that this was not a river in undisturbed condition. Preferential flow paths obviously existed due to maintained pathways. Sturt (1844) continued until having to decide whether to turn to the NW or S at the junction of 'Delangen', the Edwards River.

"We were therefore obliged to cross the Hume a little alone the junction of the small stream which had stopped us. On the left bank, however, we were still in the midst of reeds, through which we could not have pushed but for the narrow lanes made in them by the natives. We could not, however, approach the river for two days, and when we again came upon it, it was just issuing from a great marsh; its waters were muddy, and its channel considerably diminished. Instead, however, of holding a course to the westward, the Hume at this point suddenly changed it to the eastward of S., flowing through a barren country of white tenacious clay, above the reach of flood, but of the most gloomy character. It had just been fired by natives: the trees were scathed to their very summits, and the trunks of those which had fallen were smoking on the ground." (Sturt 1844)

Again, this account of the Barmah indicates the predominance of reeds, and Aboriginal burning practices. It confirms the narrowing of the channel dimensions as the river approaches the Edwards River.

Sturt (1899) also recounts this section of the journey whilst suggesting that the Hume/Murray varies in width between 80 to 100 yards (70 to 90 m), and that is navigable for its whole course. However, it is noted that sudden freshes and an immense quantity of timber in the bed would make navigation dangerous.

Hodgkinson (1856) describes the region as:

"Between the Murray and Broken Creek (which is a long but ill-defined anabranch connecting the Broken River with the Reed Beds of the Murray Ovens, near Moira there is an extensive tract of low level country, wooded by the box variety of Eucalyptus, with an occasional appearance of Banksia, Callitris Pyramidalis, Casuarina Torulosa, Casuarina Paludosa, Exocarpus Cupressiformis, and some of the Acacia tribe. The western portion of this level forest country is, however, diversified by many open grassy plains varying in extent from about one hundred acres to several thousands of acres. Some of these plains are very beautiful, their irregular but well-defined margins being fringed by the graceful Callitris and Casuarina. A dense underwood pervades much of the box forest, and I may here remark that the forest land generally, both on the New South Wales and Victorian sides of the Murray, is rapidly deteriorating as regards its grazing capabilities, owing to the great increase of scrub and underwood consequent on the partial cessation of the bush fires which formerly checked their growth." (Hodgkinson 1856 p.5)

This suggests that Aboriginal burning practices had modified the condition of the area using fire and that there were large areas of grassy plains as opposed to the current forest. Hodgkinson (1856) also discusses the wood load in the Murray. This is probably before extensive desnagging had occurred.

"At some of the bends of the river, I noticed great accumulations of snags and driftwood almost entirely blocking up the channel, and I therefore cannot sufficiently express my admiration of the energetic resolution which must have been displayed by Captain Cadell, in effecting the first accent of the Upper Murray, at a period when the low state of the river must have exposed the Lady Augusta steam tug, to continual risk of destruction from the huge logs and projecting snags that bristled up in all parts of the stream.

The navigation of the Murray from the Ovens to the confluence of the Goulburn, which is 274, miles by water from Albury, is very much less impeded by snags than from Albury to the Ovens."

"From the Gulpha (now called Gulpa) *to a point a few miles below Lake Moira, the Murray meanders through reed beds, and its channel is very free from snags. When the wooded flats recommence, the reaches of the river still continue unobstructed by any large accumulations of snags as far down as Echuca."* (Hodgkinson 1856 p.10)

The River Murray appears to have had a high instream load of large wood from Albury to the confluence with the Ovens River. Further downstream, within the Barmah Forest the channel dimensions decreased and so did the loads of instream large wood. This may be as a result of lower densities of riparian trees compared to the current situation, as reed beds and grasslands appeared to have been more extensive.

8.3 Desnagging of the reach.

Hodgkinson (1856, p.10) indicates that the River Murray Navigation Company had been given money to desnag around Barnawartha and Wahgunyah. A combination of approaches was initially used. The depth of draft needed for a loaded barge was 2 ft 9 inches or 0.84 m. Logs were cut at low water in the channel, and Captain Cadel also used the Grappler (**Figure 8-1**) to lift large wood out of onto the channel banks.

The Victorian barge operations winched the snags onto the top of the banks. There were claims that the snags left on the channel banks were washed back into the channel. This would have meant that there may have been a redistribution rather than total removal initially. Some of the snags on the banks, floodplain and in channel were also burnt to stop this possible reintroduction into the river.

Figure 8-1. *Side view of 'P.S. Grappler' at work snagging, removing fallen trees and obstructions from the river. Built at Echuca, 1858. Launched on the 1.2.1858. Government owned boat for snagging. From 1878 was used as a police station at North West Bend, Morgan. Converted to a dredge in 1880. (Godson number 9A/34). (Courtesy of the State Library of South Australia).*

The Royal Commission in 1867 was set up *"To examine into and report upon the best means to of clearing the River Murray etc."* and has much evidence that discusses the snags in the reach (Parliament of South Australia 1882). At that time, the Murray up as far as Echuca was considered good for navigation due to desnagging. From Echuca to Lake Moira was not. Then from Lake Moira to Yielima was '*pretty good running*'. Upstream of Yielima for 60 miles it has been '*very bad*' but desnagging has been commenced. Around Ulupna it had been cleared but there was a bad section just upstream and then it was reasonably clear to Tocumwal. Yarrawonga to Mulwala also had bad spots.

Already by 1867 the geomorphic consequences from the desnagging had been observed. The channel running through Lake Moira was completely cleared for 10 miles (16 km). Even at low flows the channel had deepened, eroding the sand, and exhuming buried large wood. This exposure required yet more desnagging to take place.

"Presuming the river was cleared, as you suggest and buoyed, can you mention for how many months you suppose the river would be navigable in the year?

– From April to about February, and it might be longer. The channel might become so deepened by removing these snags, and the sand accumulating about the snags. I know from experience that it washes away; I saw it when the Grappler was here. It washes a channel five or six feet very quickly, and if the sand is removed it must accumulate in some other place, and the question is whether it is not extended all along the bottom." (Parliament of South Australia 1882 p.34)

In 1864 from 7th May to 31st December there were 767 trees taken out of the stream whilst in the subsequent year (1865) 3,903 were taken out (Parliament of South Australia. 1882). In 1866 there were 3,655 snags extracted and put on the bank. It is not reported over what length of stream these works were occurring, but it is calculated that a 1,093,209 cubic ft or 30,956 m^3 of wood was removed from the channel bed.

Gippel and Lucas (2002) describe the snagging operations used to reduce channel roughness and improve flow conveyance since 1953. Between Picnic Point and Barmah desnagging between 1953 and 1963 initially also involved removing all trees within 4 m of the bank. The expense of this meant that later on only trees likely to fall in the river were removed.

There was another phase of desnagging from 1976 to 1987 (Gippel and Lucas 2002), however it was unclear the exact extent of the works. It was proposed for the reach from Tocumwal to Echuca but also appears to have included the reach from Hume Dam to Yarrawonga. The operations reportedly both removed snags and lopped encroaching willows.

8.4 Changes in the sources of bed sediment from desnagging

The removal of large wood from the channel caused channel incision. This would have mobilised sediment held in longer term storage into active transport in the river. The supply of sediment from desnagging would both be in the reach and from upstream, however, once Yarrawonga Weir was built it would have been from just within the reach. It is likely that most of the incision and release of bed sediment was during the first extensive desnagging efforts in the 1860s.

Felling of riparian trees and the removal of large wood near to the banks is also likely to have increased the amount of bank erosion, however, there is little evidence to substantiate this. The changes are most likely to have occurred in Reach 1 where the channel has been more laterally active and the riparian wood loads were greater.

8.5 Changes in the processes that affect bedload transport rates from desnagging

Removing large wood decreases the channel roughness and increases the flow velocity near the bed and on the banks. This is part of the reason the channel incised when large wood was removed. The resulting channel would have been a more efficient transporter of sand with less storage. Gippel and Lucas (2002) reported that the desnagging program from 1958 to 1963 indicated that the capacity at the Choke increased between 10-20 %. However, it would be expected that the change from reference conditions in the first desnagging efforts would have resulted in a larger difference in capacity. It is unlikely that in a channel with reference wood loads that dunes of sand would occur to the same extent in the current SBP data.

8.6 Conclusions

The Barmah Forest in its pre-European state was modified by Aboriginal burning practices and contained more grasslands and reedbeds than today. This would have meant a lower local supply of riparian large wood and consequently lower instream wood loads. Upstream, especially close to the tributary junction with the Ovens, the large wood loads were much higher. The transportation of this upstream supply was likely to be limited due to the high density of eucalypts that make them sink (Stout *et al.* 2018). Reference loads would have, therefore, been lower in the Barmah Choke than upstream closer to the Ovens River.

The desnagging of the channel over multiple time periods would have decreased the roughness in the channel. This would have resulted in an increase in bed shear stress. At the same time the cohesion of the sediment, as a result of being bound around the wood structures, would also be removed. This is why, even at low flows, the sand would have been mobilised and redistributed. However, due to the lower reference conditions of wood loads in Reach 2 the degree of change would have been greater in Reach 1.

The travel distances of the mobilised sediment are unclear. Were they transported out the reach creating whole scale channel enlargement, did the sediment redistribute slowly over the entire reach, or were there points of deposition that were long-term stores? All these probably occurred. However, the nature a DFS system means sediment redistribution was the most likely.

Desnagging would have occurred not only in the River Murray but also in the large tributaries. This would have created a series of pulses of sediment entering the channel. At the same time gold mining was producing bed sediment. It may be that while sediment was being evacuated out of the River Murray enlarging the channel there was also sediment being mobilized from mining, land clearance and desnagging that buffered bed level changes.

What is clear is that the channel did enlarge in width from 1876 to 1981 upstream of Bullatale Creek (Rutherfurd and Kenyon 2005). This widening was more significant in the 50 km downstream of Yarrawonga Weir. The survey in 1876 was probably just after the first desnagging of Reaches 1 and 2, so the channel would have been in the process of enlargement. Hence, a small proportion of the sediment estimated to have been mobilized from bank erosion within the reach was likely to have been the result of desnagging.

Table 8-1 Summary Box 7

- The reference condition for large wood was for high loadings near to the junction of the Ovens River, however loads were significantly lower close to the Barmah Choke. This was probably because of more extensive reed beds and grasslands than there are presently.

- Desnagging was initially for navigation in the River Murray. Wood was pulled out of the channel or cut down in-channel. This would have reduced the roughness of the channel, decreased bed cohesion and increased flow velocities, causing erosion.

- Observations from this first desnagging of the River Murray discuss the channel rapidly deepening even at low flows.

- Tributaries of the River Murray were also desnagged and this would have resulted in non-sequential pulses of sediment entering the main channel.

- The increase in channel capacity due to erosion of the channel from desnagging may have been mediated by the increase in sediment supply from land clearance and mining.

- Continued episodes of desnagging will have caused fluctuations in the rates of bedload transport.

9 Overall Conclusions

9.1 Evidence for a change in channel capacity at Picnic Point

The initiation of this investigation was a decrease in flow capacity from the 1980s based on the relationship between flow stages at Picnic Point and discharges at the gauge downstream of Yarrawonga Weir. The SBP data (SA Water 2020; 2021a; 2021b) suggested a loss of cross-sectional area in the channel from bed sediment, notably at river offtakes as a result of decreased sediment transport capacities. The 2018 bathymetric data (Water Technology 2020) supports this. The most detailed available evidence based on the LiDAR derived DoD between 2001 and 2016 (Water Technology 2020) shows limited planform changes in sinuosity, number of channels, and channel width in the Barmah-Millewa Forest. This would indicate that either the levees are now less effective but keeping the same cross-sectional form and/or there is an accumulation of bed sediment in the channel.

The type of river is a distributive fluvial system that loses capacity in the downstream direction. This type of channel is sensitive to changes in transport capacity and sediment supply. A decrease in channel transport capacity or an increase in sediment supply are likely to cause relatively rapid aggradation. The history of channel disturbance upstream post-European settlement suggests that there has been an increase in the amount of coarse sand sized sediment transported to the Choke and that the sand is currently aggrading between Bullatale Creek and Picnic Point.

9.2 The post-disturbance riverbed sediment conditions for Reaches 1 and 2

This study has estimated that there is at least 20 million m^3 of coarse sand on the riverbed between Yarrawonga Weir and Picnic Point. The data quantified as part of this study has allowed the following conclusions to be reached about its mobilization (**Table 9-1**), transport, distribution, and storage.

Table 9-1. *Estimated volumes of coarse sediment mobilized into the reach between the current location of Yarrawonga Weir and Picnic Point.*

Source of coarse sand	**Volume of coarse sediment (million m^3)**
Upstream gold mining	124.8
Upstream land clearance: bank erosion and gullying	16.9
Bank erosion within the reach	2.3
Bar erosion within the reach	1.4

9.2.1 Inputs from upstream

These would have initially increased as a result of land clearance triggered bank erosion and gullying as well as sediment produced as a result of historic gold mining. The combination of these processes was estimated to increase the coarse bedload from a pre-disturbance rate of 140,000 m^3/yr by over 30 times to a rate of

4,430,000 m^3/yr. The total volume mobilized, without taking into account subsequent deposition upstream of Yarrawonga Weir, was 141.7 million m^3 (**Table 9-1**). This was over 7 times the volume of coarse sand measured in the riverbed of Reaches 1 and 2.

The construction and filling of Hume Dam in 1934, followed by Yarrawonga Weir in 1939, resulted in the ceasing of bedload transport from the River Murray into Reach 1.

9.2.2 Inputs within the reaches

The absence of major tributaries in reaches, means that the main sources of coarse sand were considered to be from riverbank and point bar erosion. Elevated rates of erosion may have resulted from a combination of river regulation, desnagging and riparian vegetation clearance. These were estimated to have produced 3.7 million m^3 of coarse sand (**Table 9-1**). These local sources may have contributed to the >20 million m^3 of coarse sand on the riverbed, but on their own they cannot account for the whole volume of excess sediment.

9.2.3 Outputs within the reaches

There were no significant outputs of coarse sand identified within Reaches 1 and 2.

9.2.4 Outputs downstream

Whilst not the focus of this study, Gower *et al.* (2020) have modelled the sediment transport through Reach 2 and suggest that under regulated conditions 100,000 m^3/yr would be transported out from Picnic Point.

9.2.5 Contribution to reach bedload

The bedload was distributed with 16 million m^3 in Reach 1 and 7 million m^3 in Reach 2. Downstream of Yarrawonga Weir there is bed armouring that has protected the sediment beneath from erosion. The volumes in 10 km segments of the channel were reasonably homogeneous upstream of Bullatale Creek. Downstream, in Reach 2, the average section depths increased but the overall volume decreased as a result of the reduced channel bed area. Sediment accumulation was observed by Gower *et al.* (2020) to be greatest near to effluent offtakes.

9.3 Confidence of geomorphic changes based on the available data

The review of currently available evidence has been categorised into levels of confidence based around the amount of supporting evidence (multiple lines of evidence). It is hoped that this categorisation aids in both understanding the level of confidence in the final conclusion and also shows where there are gaps in the data to be filled where possible.

High Confidence

1. There has been a change in volume and proportion of the riverbed sediment that is coarse sand sized compared to pre-European reference conditions.
2. Meander pools have filled with sand over 4 metres in depth and this would not occur in the rivers undisturbed state.
3. Bed sediment has been trapped by Hume Dam and Yarrawonga Weir since their construction. No sand sized sediment has passed through the Hume Dam since 1936 and Yarrawonga Weir since 1939.
4. High loads of coarse sand were introduced into the River Murray downstream of Yarrawonga Weir before Lake Mulwala was filled in 1939.
5. Bankfull widths have increased between 1876 and 1981, mainly between Yarrawonga Weir and Bullatale Creek.
6. Bank erosion and gullying in upstream catchments, because of land clearance, supplied coarse sand into the bed of the Murray in Reaches 1 and 2, as did historic gold mining.
7. Bank and point bar erosion in Reaches 1 and 2 are not responsible for all of the coarse sand bed sediment and some must have been supplied from upstream of Yarrawonga Weir.
8. The coarse sand measured by the SBP came from a combination of different sources including upstream historic gold mining, gullying and bank erosion from land clearance, alongside bank and bar erosion in Reaches 1 and 2.
9. Bed sediment was disturbed, made more mobile, and the channel enlarged because of desnagging.
10. Recent flooding has not been responsible for the volume of coarse sand in the riverbed.

Medium Confidence

1. The majority of the bed sediment came from historic gold mining combined with gullying and bank erosion as a result of land clearance upstream of Yarrawonga Weir.
2. Regulation was responsible for some of the channel enlargement that has occurred downstream of Yarrawonga Weir alongside bed armouring.
3. That the particle size distribution and stratigraphy in the riverbanks downstream of Bullatale Creek can be quantified.
4. The particle size distribution of the bed sediment at different depths is understood.
5. Sediment that has the chemical signature indicating a historic mining source has aggraded in the Barmah-Millewa Forest floodplain.

Low Confidence

1. The pre-European condition of the bed including the volume of sediment transported, the variability in transport over time, pool depths and the particle size of bed sediment.
2. The pre-European budget for large wood, especially around Picnic Point.
3. The extent of bed incision as a result of the first desnagging within Reaches 1 and 2.
4. The extent of bed armouring downstream of Yarrawonga Weir.
5. The chronology of sediment volumes, sizes and heavy metals trapped by Lake Mulwala over time.
6. The sedimentary and stratigraphic composition of riverbanks from Yarrawonga Weir to Bullatale Creek.
7. The volume, size and timing of sediment that was supplied to the reach from gold mined tributaries.
8. The volume and particle size distributions of sediment that gold dredging introduced into the Murray.
9. Travel times of coarse sand from Yarrawonga Weir to Bullatale Creek.

9.4 Proposed timeline of coarse sand on the riverbed from Yarrawonga Weir to Picnic Point

9.4.1 Baseline or pre-European reference conditions.

The channel was a meandering river with sandy point bars and a 3 km wide floodplain between Yarrawonga to Bullatale Creek. This part of the river would have slowly migrated across the floodplain forming meander cutoffs. The sediment load under pre-European settlement conditions was expected to have been low with a very small proportion being the bed sediment of sands and some gravels, whilst the majority would have been the suspended load of silts and clays. There were limited sediment inputs from tributaries downstream of what is now the site of Yarrawonga Weir, and most of the bed sediment would have come from the upper River Murray. There was historically a high volume of large wood (snags) in Reaches 1 and 2 and these would have produced a riverbed with relatively high roughness and elevation complexity (**Figure 9-1**).

Downstream of Bullatale Creek the channel is sitting on an ancient low angled alluvial fan. It has become a distributive fluvial system with the channel losing flow in the downstream direction to effluents. The channel narrows and become shallower. The effluents were at multiple elevations in the riverbank above the bed of the River Murray. Some of the lower, bigger, effluents may have taken a proportion of the bedload as well as flow. As the channel narrowed and lost flow, it becomes less and less able to transport bed sediment and so aggraded the riverbed. This aggradation would cause the channel to become inefficient to transport flow and it would eventually avulse, forming a new channel on the floodplain.

The load of large wood in the channel would probably have reduced in the downstream direction as there are accounts that the lower part of Reach 2 was dominated by rushes and grassy plains rather than the red gum forest that is present today. The rushes would be unlikely in a degrading system, and more likely to occur in areas with modest aggradation. The budget of large wood supplied to the channel at Picnic Point in pre-disturbance conditions remains unclear.

The pools in the river would have been expected to be deeper compared to the rest of the channel most of the time. They may have periodically filled by a small amount during periods of lower flows and then flushed out during high flows. Pools are usually maintained by the flow regime so that they remain as deep sections of the channel. The SBP and bathymetric data both indicate that the pools have infilled throughout the survey extent, and the 2020 and 2021 SBP indicate that there is on average 1.22 m of mobile coarse sand on the channel bed from Yarrawonga Weir to Picnic Point. There appears to have been less coarse sand in the channel under reference conditions, but we do not know the reference grain size distribution of bed sediment and its depth in the channel. Whilst we do have information on the channel dimensions and planform there is little information historically, other than anecdotal accounts, on the variability of bed forms in the channel. The fluxes of bed sediment both natural and anthropogenic are poorly understood in this reach over time.

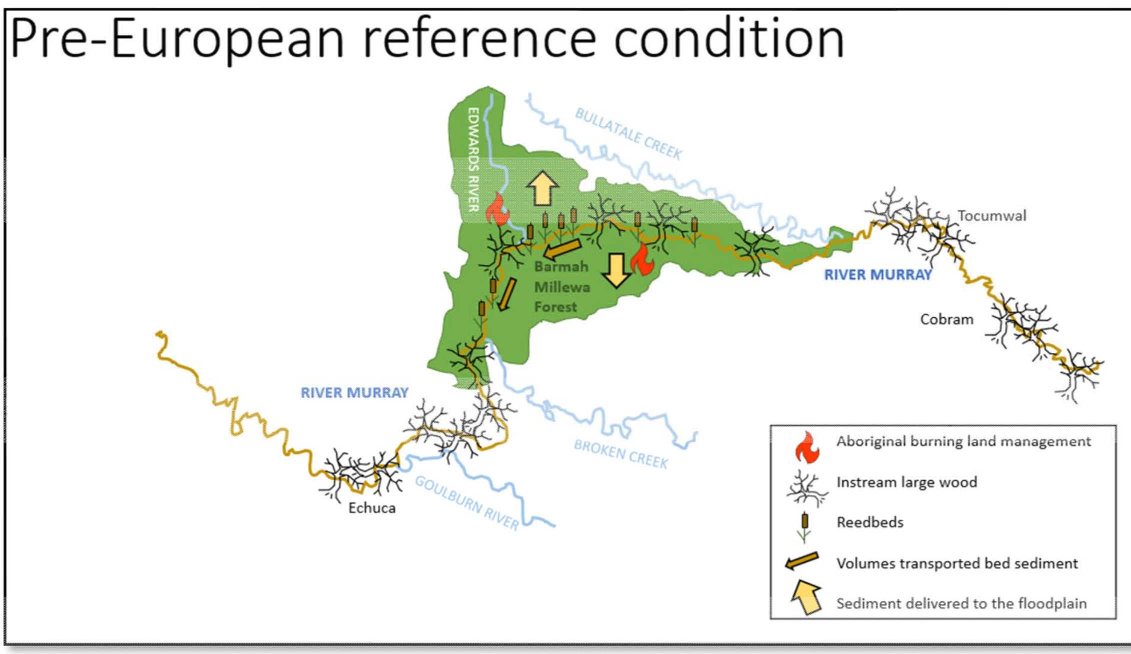

***Figure 9-1**. The pre-European reference condition of the River Murray and Barmah-Millewa Forest. The River Murray is brown to signify that it conveyed sediment, and the width of the line and arrows indicate relative volumes of sediment, the lighter colour being mainly suspended sediment. Snags were present in the channel, rushes were more extensive, sediment volumes into the reach were low and proportionally higher in suspended sediment with high losses onto the floodplain, land management included Aboriginal burning.*

9.4.2 A summary of the changes in the sources of bed sediment.

There are no major tributaries between Yarrawonga Weir to Picnic Point that would supply significant volumes of coarse sands. No other local sources of coarse sand have been identified in Reaches 1 and 2 and as such the main source of coarse sand sized sediment would have been from upstream of Yarrawonga.

Before impoundment land clearance and gold mining supplied more than 200 times the pre disturbance yield of sediment (**Figure 9-2**). Land clearing and mining often occurred at the same time, with a peak in the numbers of miners in the 1860s. The peak in mining sediment yields, pre-dredging, were in the 1880s (Davies *et al.* 2018). These peaks in mining activity corresponded to wet climatic periods which would likely be better at transporting sediment downstream. It is likely that there were a series of pulses of sediment into Reach 1 that were long and low in elevation, based around the fact that coarse sand sized sediment would be stored and reworked in many cases before it ended up in the River Murray.

Desnagging would have caused bed deepening, and along with vegetation clearance along the banks to reduce large wood inputs, it would have increased the rate of bed and bank erosion. Both the bed and banks would have supplied sediment in the reach, and from the desnagged reaches upstream.

The major change in the source of bed sediment would have been the building of Hume Dam Wall (1934) and Yarrawonga Weir (1939) (**Figure 9-3**). They block nearly all the downstream transport of course bed sediment, resulting in no bed sediment supply out of Yarrawonga Weir. This would mean that any coarse sand in Reaches 1 and 2 must have entered before 1939 or come from sources within the reach.

After impoundment of both Lake Hume and Mulwala there appears to be low rates of sand deposition into the reservoirs. There are still sources of sand that may be transported into Hume Dam and Lake Mulwala. These include the sediment slug downstream of the Eldorado dredge on Reedy Creek, a tributary of the Ovens River. However, current supplies of sand from the catchment are much lower than they would have been historically during land clearance and gold mining and are likely to be more extensively managed.

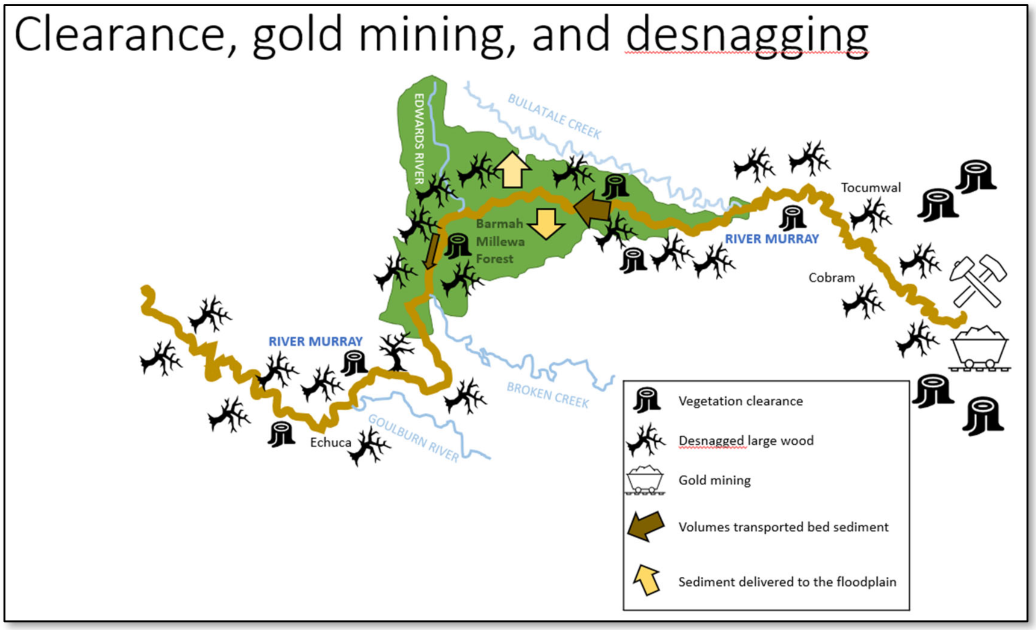

Figure 9-2. *The pre-regulation (1850-1930) condition of the River Murray and Barmah-Millewa Forest. The River Murray is brown to signify that it conveyed sediment, and the width of the line and arrows indicate higher volumes of sediment compared to reference. Catchment sediment increases were a result of land clearance and gold mining. Desnagging was extensive as was clearance of riparian large trees. Bed sediment is coarser (darker) and accumulating in the reach as the conveyance through the Choke is low. Some sand was contributed to the floodplain and effluents.*

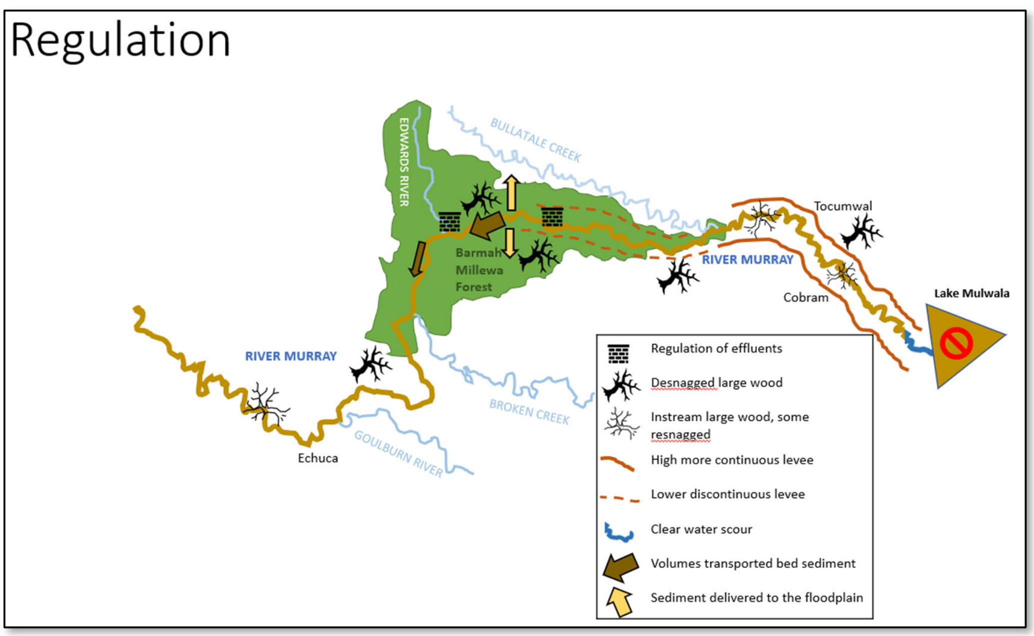

Figure 9-3. *The regulated (post-1930) condition of the River Murray and Barmah Millewa Forest. The River Murray is brown to signify that it conveyed sediment, and the width of the line and arrows indicate higher volumes of sediment compared to reference but lower than pre-regulation. Upstream bed sediment supply was stopped by Lake Mulwala, and some clearwater scour has occurred shown in blue. Levees are shown in orange and are less significant in the forest shown by the dashed line. Effluents are regulated shown by the walls. Desnagging has occurred as well as snagging. The arrows suggest the bed sediment has accumulated further downstream as a consequence of upstream supply exceeding downstream transport capacity.*

The >20 million m^3 of coarse sand from Yarrawonga Weir to Picnic Point could, therefore, have come from several different sources during two different time periods:

Time period 1: Prefilling of Hume Dam in 1936, and Lake Mulwala in 1939.

a. Gold mining in all catchments upstream of Picnic Point (sediment supply area 1).
b. Bank erosion and gullying because of land clearance in all catchments upstream of Picnic Point (sediment supply area 1).
c. Bed and bank erosion because of desnagging in all catchments upstream of Picnic Point (sediment supply area 1).

Time period 2: Post the filling of Lake Mulwala in 1939.

a. Bed, bar, and bank erosion caused by regulation from Yarrawonga Weir to Picnic Point.
b. Bed, bar, and bank erosion because of desnagging from Yarrawonga Weir to Picnic Point.

The volumes of coarse sand estimated to have been mobilized in time period 2 (**Table 9-1**) were insufficient to explain the >20 million m^3 of bedload in the River Murray. Upstream supplies of bedload before the construction of Lakes Hume and Mulwala could have produced seven times the volume of bedload between Yarrawonga Weir and Picnic Point. These data suggest that gold mining and erosion from land clearance are likely to be the dominant sources of the current bedload. However, the fact that bedload naturally accumulates in this distributive fluvial system means that all the coarse sand sources shown in **Table 9-1** would act in combination to form the current bedload.

9.4.3 A summary of the changes in the processes that affect bedload transport rates

There appears to be a reduction in the frequency of climatically driven flooding. At the Tocumwal gauge most of the changes in bed levels have occurred after flood events. This would indicate that sediment on the bed is being transported slowly downstream.

The regulation of effluents means that the loss of flow downstream has decreased from pre-regulation conditions. This should mean that the bedload transport rates should be more efficient. This may result in sand being transported further downstream, although still predominantly deposited in the Choke. However, the reduction in flood peaks because of regulation has been suggested by Gower *et al.* (2020) to reduce the transport of sediment through the Choke.

The lower large wood loads in the channel mean there is less storage of bed sediment in the channel and again a more efficient rate of transport downstream.

9.5 A synthesis of how changes in bed sediment inputs and transport create the current conditions from Yarrawonga Weir to Picnic Point

The current loads of bed sediment have a greater volume of coarse sand sized sediment than would be expected in the reference condition for this reach. Multiple lines of evidence suggest that the excess sand has been mobilized because of anthropogenic disturbances. Historical gold mining derived sediment, gully and bank erosion from upstream land clearance, and more local bed and bank erosion from desnagging could all have a caused a long low pulse like a sheet of sand, or several more discrete pulses of sediment (Sims and Rutherfurd 2017) that may have passed the current position of Yarrawonga Weir before Lake Mulwala was filled in 1939. After this point, more minor local sources between the weir and Picnic Point could have added to the existing excess of sand sized sediment.

Regulation in the channel now means that overall a lower range of flows are passed downstream from Yarrawonga Weir and there appear to be lower magnitude and less frequent floods. These flows have less opportunity to interact with long-term sediment stores, such as the upper elevation of point bars. The riverbed has currently relatively low amounts of large wood meaning bed roughness has been reduced. The sediment that is in the Choke now is being slightly more efficiently transported by regulated flows, however, larger reductions in flood magnitudes have meant that the rate of deposition has increased (Gower *et al.* 2020).

The upstream supply of bed sediment has been cut off by Yarrawonga Weir. The evidence suggests that this has caused some enlargement of the channel directly downstream alongside armouring of the bed. It is not known how far the armouring extends downstream, but it is estimated that that it is around 2 km. The coarse sand downstream of the armoured layer is being transported towards the Choke. The lack of large wood in the reach means that storage on the bed is more limited and transport downstream is very slow but effective.

Aggradation upstream of the Choke can be the result of two processes:

1. The rate of bed sediment being mobilized from upstream.
2. The transport capacity of the channel upstream and at the Choke.

The current deepest bed thicknesses have been measured around Picnic Point and this area appears to be an optimal point where the delivery of bed sediment exceeds the transport capacity.

There may be fluctuations in the rate that bed sediment arrives at Picnic Point as a result of changes in transport capacity from different flows and variation in the amount of large wood in the channel. These may cause mini pulses of sediment to pass through Picnic Point that could possibly explain some of the variations in flow capacity noted by Gippel and Lucas (2002).

9.6 Future trajectory

9.6.1 Starting position

There appears to have been the potential for larger fluxes of bed sediment in the reach before the impoundment upstream because of activities including desnagging, land clearance and gold mining. One of the first changes to the riverbed as a result of an increased supply of coarse sand would have been the filling of the pools. This filling would have progressed from upstream to downstream in Reaches 1 and 2.

Gippel and Lucas (2002) describe fluctuations in the capacity of the Choke between 1992 and 2002. It is unclear the exact reasons why, or if, the transport capacity of the Choke has been consistently exceeded at this point in time. Regulated flows have relied on the capacity of the Choke for decades, and research by HARC (2020) has shown that the frequency of near or above capacity flows during January to April 1985 – 2019 has in general not increased regulated flows through the Choke. Impoundment has been in place since 1934 at Hume Dam and 1939 at Yarrawonga Weir and there have been levees constructed since before this. The 6th highest flow on record at Tocumwal was recorded in 1993, and perhaps this was sufficient to move the coarse sand downstream so that it had a greater influence on the Choke.

9.6.2 Projections for the next 10 years

In the absence of a period of wet/flood conditions, the source of the sediment is on the riverbed, and there may be some contribution from riverbank/point bar erosion. The SBP data (SA Water 2020; 2021a; 2021b) indicates that the >20 million m^3 of excess bed sediment infilled meander pools 180 km upstream of Picnic Point, so there is at least this distance available to supply sediment. Based on observations of the historic aerial imagery and specific gauge data it appears that sediment stores have started to decline in the reach downstream of Yarrawonga Weir.

Regulated flows will move bed sediment downstream and there will be minimal amount of replenishment due to Lake Mulwala stopping its input upstream. It is expected that in the upstream part of Reach 1, downstream of the armoured layer, the bed will lower and dune forms will reduce in amplitude and/or disappear. The sediment will probably spread out (disperse) and migrate downstream (translate) in Reach 1 and may result in the meander pools starting to increase in depth. The historic rates of lowering estimated from the specific gauge data was 0.012 m/yr at Yarrawonga Weir from 1970-2020 (**Figure 6-4**) and 0.005 m/yr at Tocumwal from 1974-2020 (**Figure 6-5**). If the same rates were maintained for the next decade then there would average bed lowering between 0.05-0.1 m.

The sediment mobilized from Reach 1 will build up in Reach 2. More research is needed to better estimate the rate and distribution of bed thickening. Based on the rates outlined in **Section 4.2.4.3** the bed may build up between 0.1-0.6 m in the next decade without any intervention. The rates of bed lowering upstream indicate accumulation in Reach 2 would be towards to the low end of this range. The rates could be higher if there is a period of increased flooding. As the channel decreases in depth the risk of channel avulsion will increase as will the potential for increased bank erosion in the Barmah-Millewa Forest.

If the current operations continue without several large floods, in terms of the measurable metrics of change we would expect:

1. **Channel Planform: sinuosity**
   Relatively little change, perhaps a slight decrease if the point bars margins are eroded.
2. **Channel Planform: number of channels**
   If the rates of aggradation were sufficient then an avulsion may be possible creating a daughter channel.
3. **Cross-sectional channel width**
   A small increase, perhaps triggered by a shallower riverbed depth due to aggradation increasing the shear stress on the banks. Rates would be higher on the less resistant banks in the lower parts of Reach 1 if any peak in sediment thickness migrates through this area.
4. **Cross-sectional form**
   Increasing deepening (from scour) in the downstream direction from Yarrawonga Weir and increasing shallowing (from aggradation) downstream of Bullatale Creek. Bank slopes would also increase as the channel deepens upstream and fills downstream.
5. **Bed survey: bedforms**
   Increasing sediment depths near to Picnic Point. Deepening of meander bed pools at the upstream end of the reach as sediment is moved out of storage alongside the reduction and/or stabilisation of stores of sediment in point bars upstream.

9.7 Suggested future data requirements

The following data are suggested to strengthen confidence in the predications made in this study.

- **Hydraulic modelling to estimate the likely rates and volumes of bed sediment flux between Yarrawonga Weir and Bullatale Creek.**
  Alongside an estimate of a volumetric change of channel capacity based on surveys, modelling of likely fluxes all the way from Yarrawonga Weir to Echuca may improve an understanding of both current and future states of the riverbed.
- **Observations on erosion and sediment transport in effluents.**
  This report has concentrated on the main channel of the River Murray, however, data of geomorphic conditions of effluent channels may help strengthen assumptions made about sediment size and volumes that are entering the effluents and whether this has changed over time.
- **Observations of sand sediment deposition on the floodplains of the Barmah-Millewa Forest, such as cores that show any changes over time.**
  Targeted sampling combined with the collation of existing data may help understand whether in the past 20 years rates of sedimentation have been substantially lower than during earlier periods.

Chemical analyses may confirm or deny historic gold mining input should they be undertaken concurrently.

- **Rates of aggradation and changes in chemical composition in Lake Mulwala, like that undertaken by Baldwin *et.al* (2008) in Lake Hume.**
  Whilst there is some data on the chemistry bed sediment in Lake Mulwala it is mainly fine sediment from the surface. A more focussed set of cores to explore both the rate of sediment accumulation and the chemistry of the sediment should be undertaken.
- **A survey of the riverbank sediment composition from Yarrawonga Weir to Picnic Point alongside bed particle size analysis.**
  Currently the sediment sampling has concentrated downstream of Bullatale Creek, has not included much detail on the stratigraphy of particle sizes in the riverbanks, or the particle size distribution with depth in the bed. This would enable a better understanding of the likely contribution of bed sediment from riverbank erosion, as well as a better comprehension of the processes and rates of erosion.

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Appendix 1: Estimations of coarse sand volumes in the River Murray from Yarrowonga Weir to Picnic Point

A1. The volume of mobile bed sediment derived from 2020 and 2021 SBP data

A1.1. SBP data extents

The 2020 SBP data was captured in a 24 km reach with the Barmah-Millewa Forest. The 2021 SBP data was captured in two tranches: (1) upstream between Yarrawonga Weir and Nine Panel Creek, and (2) Picnic Point to Barmah township. This means that there are three different datasets that can be combined to determine the depths of mobile riverbed sediment between Yarrawonga Weir and Picnic Point.

The SBP data has been reported a series of points along a meandering longitudinal pass across the bed of the River Murray. This means that the data is a sample of the depths of the riverbed rather than a complete coverage across the whole riverbed. The data also were limited by the water levels during the sampling as the data has been captured from a boat in the water.

A1.2. Verification of the SBP depths used to estimate bed volumes

Water Technology (2021) undertook a field verification of the SBP sediment depths using a steel probe from an anchored boat (**Figure A0-1**). The probe was inserted into the bed and pushed until a change in resistance that was considered to be the clays underlying the mobile sands.

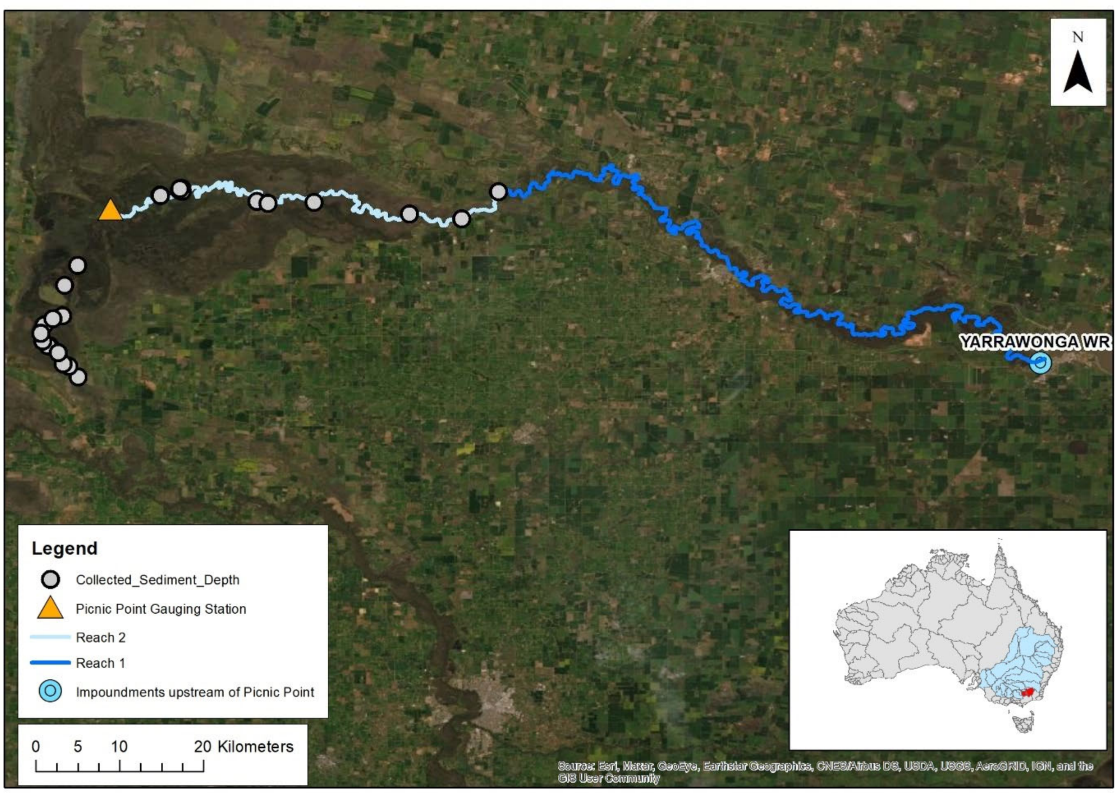

Figure A0-1*. Position of bed sediment validation sampling by Water Technology 2021.*

Three measurements were generally taken at each location to create the range of depths shown in **Table A0-1** and **Figure A0-2**.

Table A0-1. *Comparisons between the field measured sediment depths and the SBP measures (Water Technology 2021).*

Bed load depth – Field Measure (m)	Bed load depth – Sub-bottom profiling (m)
	Sub-Bottom Profiling 2020
1.38 – 1.66	1.86 – 2.09
1.60 – 2.02	0.61- 0.87
0.0	0.62 – 0.78
2.70 – 2.75	2.24 – 2.37
2.97 – 3.33	2.17 – 2.82
	Sub-Bottom Profiling 2021
1.32 - 1.45	1 - 1.25
1.63 - 2.45	0.8 - 1.25
1.3 - 1.5	1.1-1.9
0.77	1.15 - 1.55
0.6 - 0.8	1.9 - 2.55
0.24 - 0.26	0.8 - 0.95
0.6	1.04 -1.1
2.97	1.05 - 2.05
1.38 - 1.7	1.43 - 1.55
0	0.41 - 0.44
0	2.78 - 2.86
0	1.17 - 1.33
0	0.26 - 0.57
0.25 - 0.54	0.54 - 0.78
0	0.77 - 1.02
0.25	0.92 - 1.02
4.1	1 - 1.44

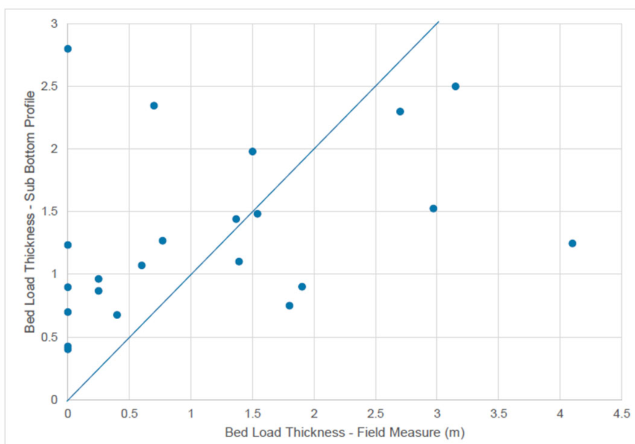

Figure A0-2. *Comparisons between the field measured sediment depths and the SBP measures (Water Technology 2021).*

To investigate if the field and remotely sensed data were significantly different, a Wilcoxon Signed Rank Test was used. The test is a non-parametric statistical test to determine if the median of two sets of paired samples were significantly different from 0.

The maximum depths that were reported were used to gauge a standard difference between datasets.

H_0 = The median difference between field and SBP depths was zero.

H_1 = the median difference is not zero.

The lowest W statistic was 87 (n = 22) and this value is higher than the critical value for a two tailed test at 90, 95 and 99 % significance levels. This indicates that the H_0 cannot be rejected and that the sample medians are not significantly different from zero. Although there were differences between field and SBP data they were not significant at 99% confidence interval. This would suggest that the volume of sand calculated using the SBP data was real and can be confidently used.

A1.3. The area of the riverbed between Yarrawonga Weir and Picnic Point

There was no available map of the extent of the riverbed to allow the SBP depths to be interpreted into a volume of sediment. Bathymetry of the River Murray was not available for the whole 2021 SBP reach from Yarrawonga Weir to Barmah township so this could not be used to delineate the bed of the channel.

To set a repeatable standard for delineating the bed using a single technique for the whole 2021 SBP reach from Yarrawonga Weir to Barmah the 2015 LiDAR was used. These data were captured over the required extent of the river from September to October 2015 which was a period of medium flows. The LiDAR does not penetrate the water, so although it does not capture the bed itself it does very clearly capture the water surface. The advantage of LiDAR over more recent satellite images is that the ground surface can more easily be seen as vegetation returns have been removed in the Digital Terrain Model (DTM). Trees overhanging the banks can influence the delineation of the bed or water surface from imagery. The water surface will be an over-estimation of the bed extent.

The LiDAR tiles were merged from Yarrawonga Weir to Barmah township. The DTM was then changed to a slope layer. This was then reclassified into above or below 0.001 degrees, as the water surface is flat whilst the riverbanks are not. A trial-and-error approach was used to determine this value to minimise the number of pixels selected and maximise the amount of the bed selected. There were sections of the river water surface that were not selected by this approach, this was due to artifacts in the data, some of which may be the result of joining multiple tiles. The gaps were sections across the whole channel extent, and not just the critical edge where the banks meet the water surface. The raster of <0.001 degrees was then clipped using a buffer of 100 m around the centreline derived from previous bankfull mapping. The raster was then converted to polygons. The gaps in the polygons were manually filled to create a continuous polygon of the water surface from Yarrawonga Weir to Barmah township. The area of the polygon could then be calculated. The polygon was also divided into 22 x 10 km reaches starting at Yarrawonga Weir so that the change in volumes downstream could be investigated. The last section near to Barmah township is shorter than 10 km in length.

A1.4. Calculations of the volume of mobile bed sediment

The areas of water surface polygons were multiplied by the average depth of the SBP data (**Table A0-2**).

Table A0-2. *Calculations of sediment volumes based on SBP data and water surface areas to approximate riverbed volumes.*

Section number	Comment	Water Surface/Bed Area (m^2)	SBP 2021 count	Min SBP depth (m)	Max SBP depth (m)	Average SBP depth (m)	Average SBP Depth including 2020 (m)	Standard deviation of SBP depths (m)	2021 SBP data volume (m^3)	2021 and 2020 gap SBP data volume (m^3)
1	Starts at Yarrawonga	1,130,255	37,738	0.11	4.82	1.27	1.27	0.71	1,436,234	1,436,234
2		1,011,394	38,233	0.11	3.63	1.18	1.18	0.41	1,197,928	1,197,928
3		1,126,734	35,055	0.14	2.99	1.17	1.17	0.39	1,314,143	1,314,143
4		1,103,434	30,510	0.24	3.22	1.26	1.26	0.44	1,389,222	1,389,222
a5		989,917	29,617	0.14	4.01	1.30	1.30	0.48	1,283,386	1,283,386
6		1,080,968	28,248	0.08	3.06	1.27	1.27	0.44	1,375,984	1,375,984
7	Next to Cobram	983,379	27,820	0.15	3.68	1.33	1.33	0.44	1,303,605	1,303,605
8		1,011,053	29,818	0.12	3.62	1.32	1.32	0.45	1,334,376	1,334,376
9		1,258,702	32,497	0.08	3.37	1.14	1.14	0.49	1,435,122	1,435,122
10	Next to Tocumwal	1,120,009	30,608	0.09	4.51	1.28	1.28	0.58	1,428,323	1,428,323
11		1,194,172	35,203	0.03	4.03	1.06	1.06	0.36	1,269,971	1,269,971
12	Ends just after Bullatale Creek	1,061,089	30,900	0.23	4.62	1.12	1.12	0.43	1,189,980	1,189,980
13		1,102,802	33,289	0.09	2.99	1.16	1.16	0.41	1,274,277	1,274,277
14		999,555	32,658	0.08	3.21	1.16	1.16	0.47	1,161,152	1,161,152
15		878,814	30,934	0.05	4.65	1.18	1.18	0.54	1,036,623	1,036,623
16		826,879	31,267	0.07	3.93	1.35	1.35	0.59	1,118,531	1,118,531
17		730,143	31,431	0.09	3.47	1.20	1.20	0.51	875,964	875,964
18		693,028	26,744	0.08	4.41	1.17	1.17	0.52	809,930	809,930
19 - 2021 incomplete	Ends at Picnic Point	637,267	11,625	0.11	4.11	1.51	1.20	0.85	965,193	767,804
20		487,961	43,033	0.08	4.90	1.50	1.50	0.79	732,063	732,063
21		526,636	36,997	0.03	3.65	1.09	1.09	0.65	571,745	571,745
22	Ends at Barmah township	374,844	19,142	0.09	3.30	0.85	0.85	0.53	317,138	317,138
	Sum 1-19	18,939,594			**Average 1-19**	1.23	1.22	**Sum 1-19**	23,199,943	23,002,554
	Sum 1-22	20,329,036			**Average 1-22**	1.22	1.21	**Sum 1-22**	24,820,889	24,623,501

Estimates were made using the averages from 2021 SBP data only with only partial data in section 19. The average 2020 SBP data for section 19 was also calculated to infill the missing data.

Using both 2020 and 2021 data:

1. From Yarrawonga Weir to Picnic Point
    a. Average depth = 1.22 m.
    b. Volume of mobile bed sediment = **23,002,554 m^3**.
2. From Yarrawonga Weir to Barmah township
    a. Average depth = 1.21 m.
    b. Volume of mobile bed sediment = **24,623,501 m^3**.

These volumes of sediment are estimates based on the best available information. So that they are not considered to be of extremely high accuracy the total volume will be reported as >**20,000,000 m^3 or >20 million m^3.**

The volume of each 10 km section is show in **Figure A0-3** and indicates higher volumes of sediment in the 10 km downstream of Yarrawonga Weir. There is then a decline in volume in section 2. From section 3 to section 10 (next to Tocumwal) the overall trend is for increasing section volumes, although there is some variability. There is then a relatively consistent decrease in section sediment volume to Barmah township.

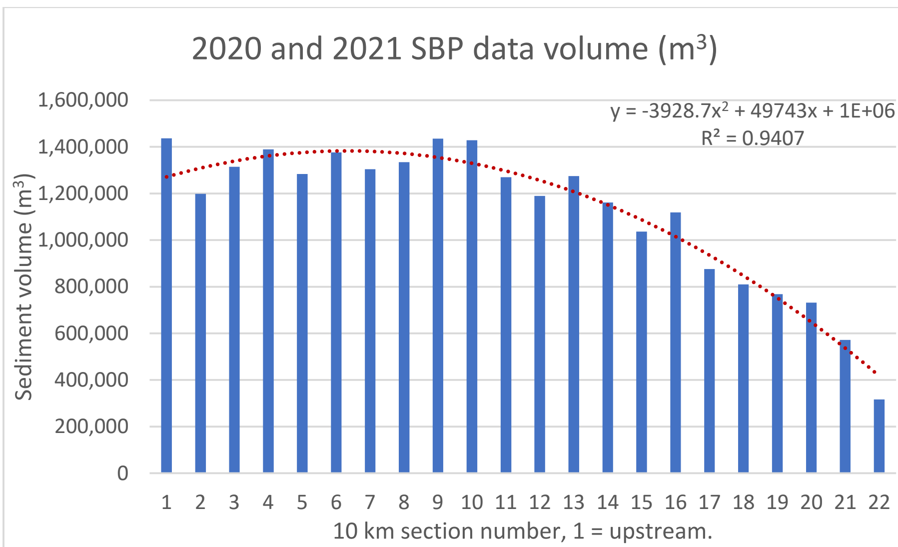

***Figure A0-3**. The volume of riverbed sediment for 10 km sections from 1=upstream starting at Yarrawonga Weir and 22=downstream finishing at Barmah township.*

A2. Calculations to determine the volume of coarse sand derived from riverbank erosion between Yarrawonga Weir and Picnic Point.

The data from **Figure A0-4** was digitised to allow the values to be extracted from Yarrawonga Weir to Picnic Point. The 2015 LiDAR was then used to repeat the bankfull width measurements at the same locations. The rates of change between 2002 and 2015 were not believable with some large rates of channel contraction that were not evident in the imagery or likely geomorphologically. The 2002 data was collected with a laser range finder with an estimated accuracy of +/- 5 m. These data were thought to be large overestimates of the bankfull width, especially between Yarrawonga Weir and Bullatale Creek. Because of this overestimation they have not been used in the rest of the calculations.

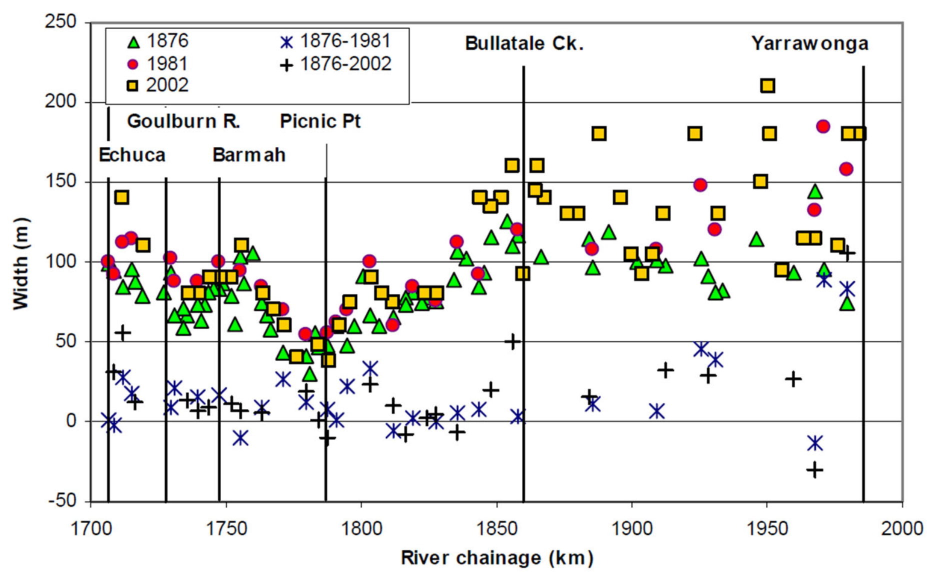

Figure A0-4. *Historical channel changes observed on the River Murray between Yarrawonga and Echuca. Crosses represent the* ***change*** *in metres between the 1876 survey width and the 1981 or 2002 survey, whilst the other shapes represent the surveyed widths (Gippel & Lucas 2002).*

The data from **Figure A0-4** showing changes between 1876 and 1981 are show in **Table A0-3**.

***Table A0-3.** Differences in channel widths from Yarrawonga Weir to Picnic Point between 1876-1981 and 1981-2015. Those values highlighted in blue were upstream of Bullatale Creek.*

Murray Chainage (km)	Difference in width 1876 to 1981 (m)	Channel width 1981 (m)	LiDAR width 2015 (m)	Difference in width 1981 to 2015
1980	83.3	158	139	-19.4
1971	89.5	185	140	-45.1
1968	-13.0	134	134	-0.2
1931	38.9	121	110	-11.1
1926	45.7	148	129	-19.4
1909	6.8	109	106	-2.7
1885	11.1	108	130	21.9
1858	3.7	120	129	8.5
1843	7.4	93	127	34.5
1835	5.6	113	94	-19.0
1828	1.0	75	92	16.8
1819	1.9	84	102	17.5
1812	-5.6	60	85	25.4
1803	32.7	101	85	-15.6
1795	21.6	70	86	15.8
1791	0.6	63	60	-2.7
1787	7.4	56	55	-0.9

The cross-sectional changes were then converted into volumetric changes by extrapolating the width changes downstream until the next cross-section by multiplying the width difference by the difference in chainage. These values were then multiplied by the median bank height reported by Rutherfurd and Kenyon (2005).

Table A0-4. *Estimates of bank erosion volumes from Yarrawonga to Picnic Point between 1876, 1981, and 2015. The data in blue were upstream of Bullatale Creek.*

Murray Chainage (km)	Channel length (m)	Median bankfull depth (m) (Rutherfurd and Kenyon 2005)	Volume of sediment 1986 to 1981(m^3)	Volume of sediment 1981 to 2015 (m^3)
1980	8,775	7	5,118,830	-1,190,748
1971	3,291	7	2,061,751	-1,038,709
1968	36,563	7	-3,317,760	-41,332
1931	5,484	7	1,492,992	-426,834
1926	16,819	7	5,377,931	-2,289,580
1909	23,766	7	1,129,618	-448,454
1885	27,422	7	2,132,846	4,208,727
1858	14,625	7	379,173	870,519
1843	8,044	5	297,921	1,385,695
1835	7,313	5	203,128	-696,288
1828	8,775	5	43,265	739,074
1819	7,313	5	67,709	640,876
1812	8,775	5	-243,754	1,113,243
1803	8,410	5	1,375,629	-656,829
1795	3,656	5	394,971	289,098
1791	3,656	5	11,285	-49,962
1787	1,294	5	47,938	-5,829
Total volume (m^3)			**16,573,475**	**2,402,667**

The volume of the eroded sediment that was coarse sand or coarser was then estimated using the data collected from (Water Technology 2021), these data were samples from between Bullatale Creek and Barmah township. Excluding the sediment taken from a sandy ledge (sample 104) that was unrepresentative of the reach, the average percentage of the banks that was coarse sand or coarser was <5%. However, the most upstream site had a higher percentage of 12.3% of coarse sand and gravels. This value was used as it was considered to provide a conservative estimate and also to better represent the bank sediment sizes between Yarrawonga Weir and Bullatale Creek.

Between 1876 and 1981 there was **1,988,817 m^3** of coarse sand or gravel supplied to the riverbed from riverbank erosion between Yarrawonga Weir and Picnic Point.

Between 1981 and 2015 there was **288,320 m³** of coarse sand or gravel supplied to the riverbed from riverbank erosion between Yarrawonga Weir and Picnic Point.

The bank erosion total contribution of coarse sand to the bed of the River Murray between Yarrawonga Weir and Picnic Point was estimated to be **2,277,137 m³.**

A3. Calculations to determine the volume of coarse sand derived from erosion of point bars between Yarrawonga Weir and Picnic Point.

As part of the study, georectification of 1940-1950s aerial photography had been undertaken. The rectification was not good enough to establish channel movement based on relative channel positions and so it was not used to determine the change in area bars based on their difference in spatial location. Instead, the unvegetated areas of sand bars in the imagery from Yarrawonga Weir to Picnic Point was undertaken and then in the current imagery from ESRI (2019) at a scale of 1:2,500. The area of bare sand without continuous vegetation has been digitised as consistently as possible. Examples of the imagery are shown in **Figure A0-5** and **Figure A0-6**.

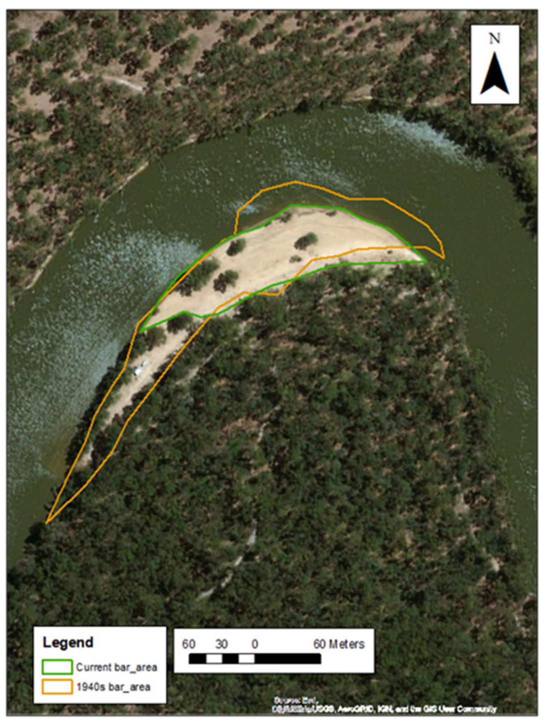

Figure A0-5. *Recent (2019) aerial imagery shown with the extent of the bar digitised from the current and 1940s imagery based on the extent of sand without continuous vegetation.*

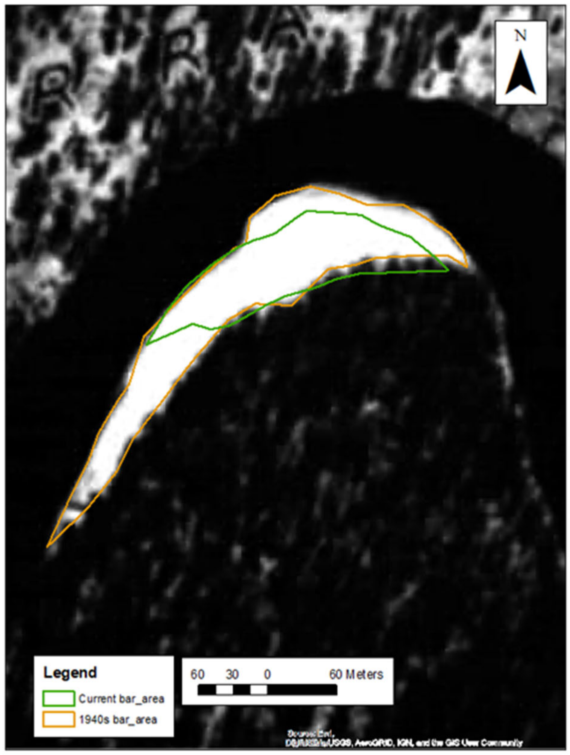

Figure A0-6. 1940s aerial imagery shown with the extent of the bar digitised from the current (2019) and 1940s imagery based on the extent of sand without continuous vegetation.

There will be errors from different water levels and the projection of images as well as the determination of 'mobile sand' or unvegetated areas. However, the gross areas and changes help clarify whether the erosion of these bars are responsible for the bed sediment.

- The area of unvegetated sand bars in the 40s – 50s imagery, not long after full regulation in 1939, was **1,491,964 m^2.**
- The area of unvegetated sand bars in the 2019 imagery was **1,095,101 m^2**
- The 'reduction' in unvegetated area was **396,863 m^2, or 27%** of the 1940s – 50s extent.

However, this reduction in area strongly appeared to be as a result of vegetation establishment of the bars rather than the erosion of the bars. It is difficult to be precise about this but in many examples the relative position of the bar appears to be similar, but the amount of vegetation has increased. This could be the result of a number of factors such as better stock exclusion, changes in flows regimes that may reduce the flux of sediment, different climatic conditions, or other land management decisions.

It was not considered that this reduction in active bar area was the result of erosion of the bars. However, there is the possibility that stabilisation of the bars by vegetation may result in regulated flows at fixed stages causing erosion of the bar margin, especially upstream. The data does not appear to support the fact that this erosion is extensive.

However, if we were to consider the loss in area to be from planform erosion then a volume of sediment eroded can be estimated. The majority of bars were upstream of Bullatale Creek, the median bankfull depth reported by Rutherfurd and Kenyon (2005) of 7 m in this area was used to provide a depth of erosion. It was assumed that the bars are at an angle of 45 degrees, which is likely an overestimate, therefore we can half the total volume calculated. This provides a volume of 1,389,020 m^3 of sediment.

The sediment samples collected by Water Technology (2021) indicated that the particle size distribution on the bars was very similar to that found on the riverbed. Hence the volume of coarse sand that could have been contributed to the riverbed between Yarrawonga Weir and Picnic Point from bar erosion would be **1,389,020 m^3**.

A4. Calculations to determine the volume of bedload derived from land use changes upstream of Yarrawonga Weir.

The volume of sediment contributed by gold mining (Davies *et al.* 2018) was based on data for the period of 1859 to 1891 in Victoria. They report the data per year for mining sediment and as do the SedNet data for post-European sediment yields (NLWRA 2001). It was assumed that this was a period of known volume of mobilization and therefore can be used as a minimum estimate of sediment contributions upstream of Yarrawonga Weir. Only the contributions from the Upper Murray, Kiewa, and Ovens basins have been included as only 16 % of the Murray-Riverina basin is upstream of Picnic Point and there would be overlap in the estimations of bank erosion from that undertaken between Yarrawonga Weir and Picnic Point.

A conversion factor of 1.6 has been used to convert tonnes of sediment to cubic metres (Davies *et al.* 2018). Only the contribution from gullies and bank erosion has been used from the NLWRA (2001) data as hillslope erosion was only modelled as a contributor of suspended sediment in their budgets. For gully and bank erosion, the same factor used by the NLWRA (2001) of 0.6 was used to estimate the proportion of the mobilized sediment that went into bedload. The multiplier was also used for gold mining.

- Estimated upstream volume of coarse sediment produced by gold mining from 1859-1891 (Upper Murray, Kiewa, Ovens) = **124,872,000 m^3.**
- Estimated upstream volume of coarse sediment produced post-European SedNet yields from 1859-1891 (Upper Murray, Kiewa, Ovens) = **16,902,335 m^3.**

A5. Summary of coarse sediment volumetric calculations

The estimated volumes of coarse sediment from different sources have been compared to the volume of coarse sand of >20 million m^3 in Reaches 1 and 2 (**Table A0-5**). Upstream gold mining produced a volume of bedload over six times the bedload volume. Bank erosion and gullying as a result of land clearance were estimated to produce 85 % of the bedload. Within the reach, bank erosion produced 11 % of the bedload and bar erosion produced 7 %.

Table A0-5. *Estimated volumes of coarse sediment mobilized into the reach between the current location of Yarrawonga Weir and Picnic Point.*

Source of coarse sand	**Volume of coarse sediment (million m^3)**
Upstream gold mining	124.8
Upstream land clearance: bank erosion and gullying	16.9
Bank erosion within the reach	2.3
Bar erosion within the reach	1.4