Geomorphic Assessment for the NSW Reconnecting River Country Program In the Murray and Murrumbidgee Rivers:

Appendix C Sub-Reach Assessments

Report for Water Infrastructure NSW, Department of Planning and Environment

This document is Appendix C of the following report:

Lauchlan Arrowsmith, C.S. Vietz, G. Wakelin-King, G. Grove, J. and Rutherfurd, I. Cheetham, M. Martin, J. Gower, T.G. Al Baky, A. Woods, K. Lam, D. (2022). Geomorphic Assessment for the NSW Reconnecting River Country Program in the Murray and Murrumbidgee Rivers, report prepared for Water Infrastructure NSW, Department of Planning and Environment

Sub-reach geomorphic assessments are provided for 30 sub-reaches located across the River Murray and Murrumbidgee River systems. For further details of the sub-reaches selected please refer to the main report

Sub-Reach 1 Geomorphic Outline – Albury Reach

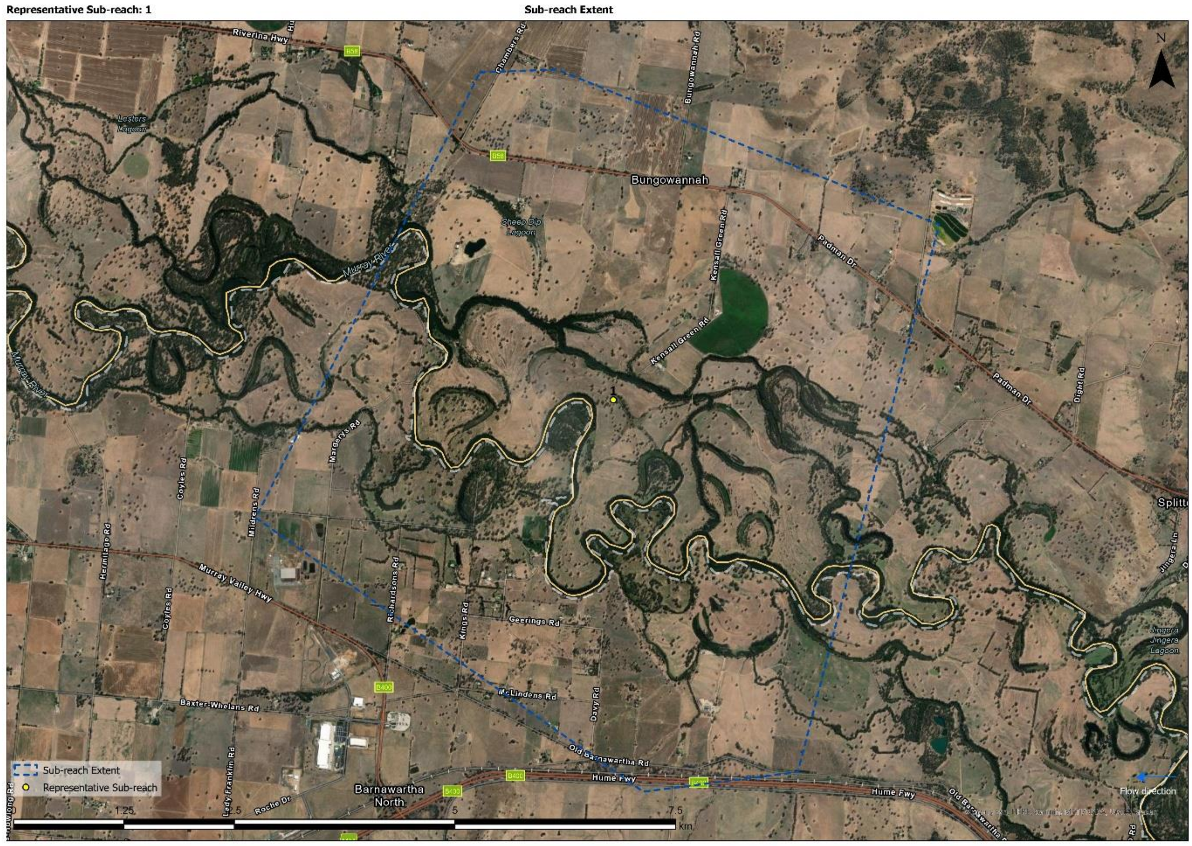

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The Murray River is a broadly a “Type 3: *mixed-load, laterally* active *anabranching river*”, (Nanson & Knighton, 1996). By definition, this means that the Murray River is characteristically a dynamic river system where:

- The meander bends are free to progress across the floodplain surface.
- Meander cut-offs are common (oxbow lakes).
- Multiple river channels can form, where a secondary channel leaves the parent river (in this case the Murray River) to re-join it further downstream (defined as an anabranch). Contemporary anabranches occur along almost the entire reach.

This description fits well to this sub-reach and the broader Albury, Howlong and Mulwala reaches.

The Dights Creek anabranch complex (sub-reach 1) is situated on the NSW floodplain, comprising multiple anabranches including Dights Creek, Yellowbelly Creek and Weidners Creek. The sub reach is situated approximately 14 km upstream of Howlong and 14 km downstream of Albury/Wodonga. Dights Creek represents a more hydraulically efficient flow path compared to the adjacent section of the Murray River. The anabranch currently captures more than 50% of the flow away from the Murray River. Works aimed at managing anabranch development have been undertaken in Dights Creek. Stream lengths of the primary anabranch network relative to the Murray River are provided in Table 1.

Table 1 Stream Length and Sinuosity Data (Ian Drummond & Associates, 1993).

Anabranch	Stream Length (km)	Sinuosity	Main Stream	Stream Length (km)	Sinuosity
Dights Creek	5.8	1.22	Murray River	11.9	1.94
Dights Creek – Yellowbelly Creek 1	7.3	1.18	Murray River	14.7	1.68
Dights Creek – Weidners Creek	9.9	1.18	Murray River	19.2	1.69

2. Channel form and processes

a. Anthropogenic Influences

Erskine *et al*. (1993) investigated channel changes on the Hume to Yarrawonga (Lake Mulwala) reach of the Murray River. They proposed that the changes having greatest influence on the physical form of the river were:

- River regulation. The extensive changes to the flow and sediment regime of the Murray River due to regulation is known to impact on the morphology of the river.
- Floods. Floods are recognized to be important agents of geomorphic change, especially the initiation and connection of anabranch channels. However, the presence of Lake Hume has influenced the frequency and duration of floods.
- De-snagging.
- Changes in riparian vegetation. Dights Creek is primarily located on freehold land and has been subject to unrestricted grazing pressures in the past.
- Boat waves. This sub reach is not subject to intense boat activity.

b. Historic changes based on the historical imagery

The Dights Creek anabranch complex (including Weidners and Yellowbelly Creeks) developed a connecting channel between its offtake point from the Murray and confluence with the Murray River at some stage between the 1850’s and 1950’s (Ian Drummond & Associates, 1993). The anabranch has developed through a combination of reoccupation of palaeochannels and knickpoint erosion between the palaeochannel features.

A review of 1961 aerial photography found that the Dights Creek channel position has largely remained the same. There are observable changes in channel width in several locations. Primary processes occurring within Dights Creek are channel widening (likely occurring in at least part due to bed deepening) and lateral migration.

The Dights Creek anabranch network has been subject to active management over the last 20 years, including the installation of instream works in combination with fencing and revegetation aimed at managing anabranch development.

Figure 2 Historic imagery (circa 1945) of the sub-reach extent

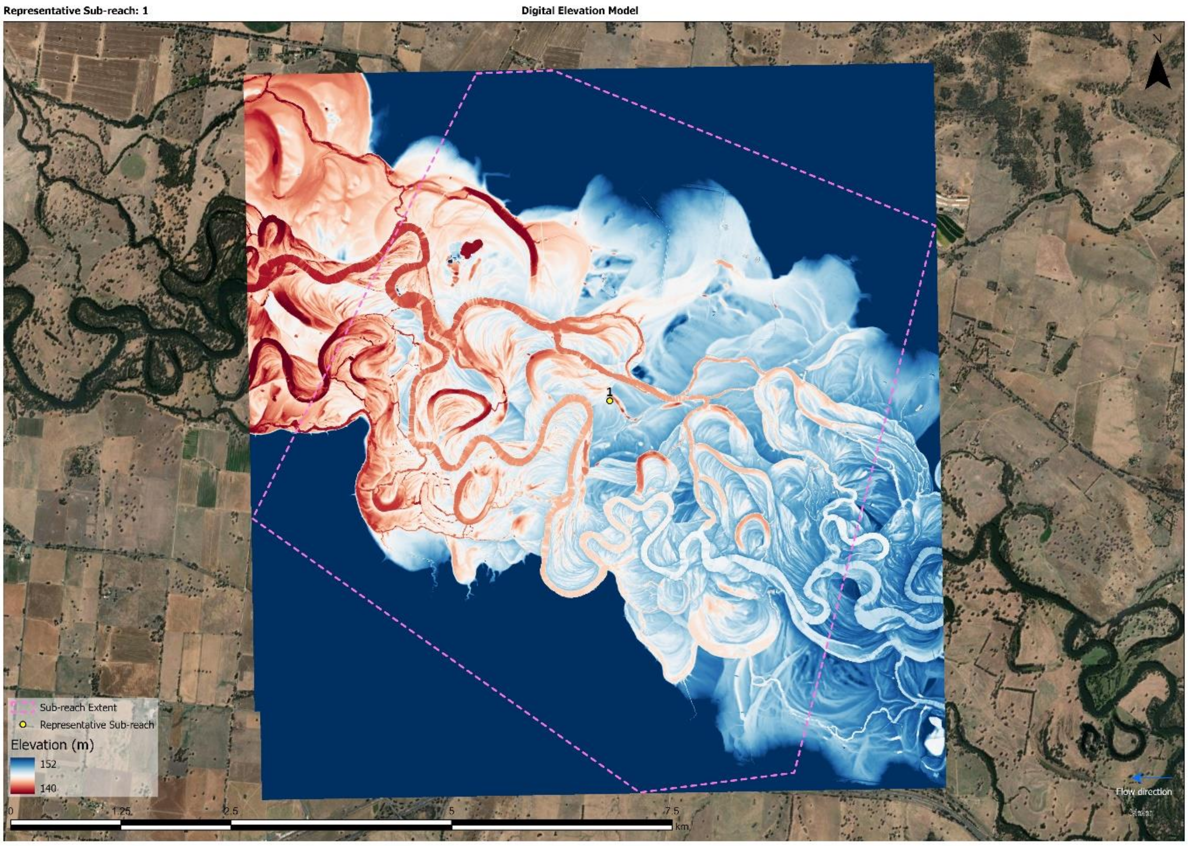

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

c. Forms (mainly based on LiDAR)

Dights Creek exhibits a diverse range of longitudinal bed morphology, including riffles, pools, runs and bars.

d. Processes

Dights Creek is significantly straighter, steeper and hence shorter than the adjacent section of the Murray River. As such, Dights Creek threatens to capture flow away from the Murray River. The creek is well developed and carries flow during both high and low regulated flow conditions.

3. Floodplain form and process

a. Anthropogenic changes

Dights Creek is primarily located on freehold land and has been subject to unrestricted grazing pressures in the past. Of recent times, stock proof fencing and revegetation works have been undertaken in the upstream third of the anabranch to manage anabranch development.

b. Hydrological connections

The anabranch network is well developed and carries flow during both high and low regulated flow conditions. The anabranch network is also well connected to the surrounding floodplain surface and inset features including palaeochannels.

Bankfull flows are around 28,000 ML/d, with increasing engagement of floodplain scroll bars and cutoffs up to 45,000 ML/d. Widespread floodplain inundation only occurs for flows > 70,000 ML/d.

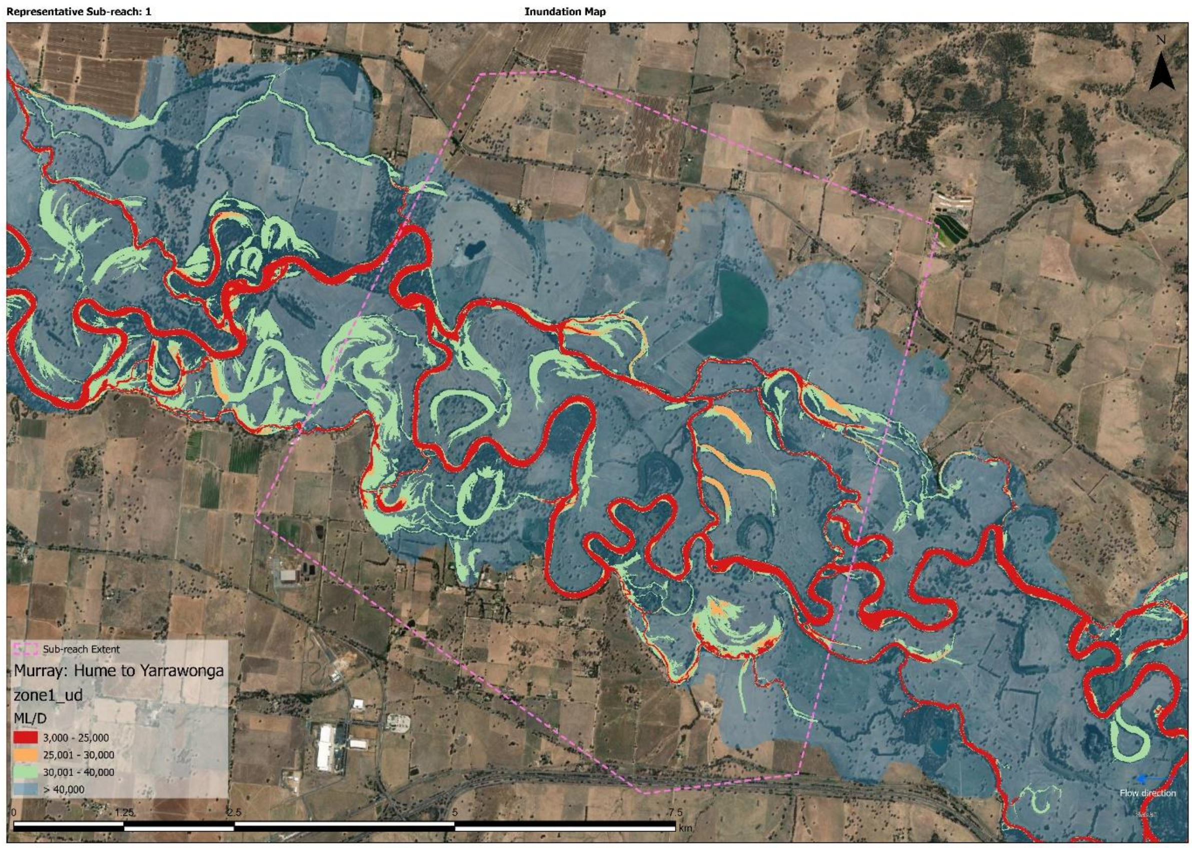

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

c. Form (mainly based on LiDAR)

The LiDAR data and aerial imagery shows a complex topographic floodplain surface, comprising palaeochannels, scroll bars and flood channels.

d. Processes

Palaeochannels are activated during sub bankfull flow events and greater. Flood channels are activated during bankfull flow events and greater. The development and evolution of anabranches involves the erosion and enlargement of a channel system, thus capturing flow from the parent channel.

4. Base case

The base case geomorphic features and processes are summarised in Table 2.

Table 2 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration / meander extension / avulsion)
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 1 are summarised in Table 4. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow options

The relaxed constraints flow options relevant to this reach are as follows:

Table 3 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Hume to Yarrawonga	25,000 @ Doctors Point (current flow limit) 30,000 40,000	River Murray and floodplain from Hume Dam to Yarrawonga Weir (NSW and VIC sides)

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

The flow thresholds for each flow category are based on the Hume to Yarrawonga section of the River Murray, using the Doctors Point gauge.

Table 4 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Sub-bankfull flows (freshes)	Sub-bankfull (high flow freshes)	Bankfull	Bankfull floodplain flow	Large floodplain inundation events
Riverbanks	Erosion	3	2	1	1	1
Cutoffs	Avulsion / meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Floodplain (> bankfull)	Sediment desposition	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.01**	**0.82**	**0.39**	**0.22**	**0.08**
Likelihood (Y45D40 events per year)		1.00	0.87	0.67	0.19	0.07
Likelihood (Y30D30 events per year)		1.00	0.92	0.60	0.21	0.08

Table 5 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.4	5.7	6%	5.7	7%
Cutoffs	4.7	5.5	17%	5.5	17%
Anabranches / Floodrunners (sub-bankfull)	3.7	4.5	22%	4.5	22%
Anabranches / Floodrunners (> bankfull)	0.9	0.8	-16%	0.9	-3%
Floodplain (> bankfull)	0.9	0.8	-16%	0.9	-3%
Average	3.1	3.4	9%	3.5	12%

The current (base case) trajectory of the reach (channel and floodplain) is likely to be ongoing anabranch development of Dights Creek. As such, Dights Creek threatens to capture flow away from the Murray River. Increases in bankfull flows and flows just above bankfull will enhance the erosion and enlargement of anabranch channel system, by capturing flow from the parent channel.

The impact score for the sub-reach reflects this potential risk – under current constraints cut-offs (avulsion / meander migration) and anabranch development have a high score in terms of the link between the feature and flow regime (namely bankfull flows and above). For the flow options (Y45D40, Y30D30) the frequency of flows particularly in the bankfull range is increased. An increase in the frequency of sub-bankfull freshes may also increase the risk of enhancing existing geomorphic processes such as bank erosion in this reach, which is also a risk under the current constraints flow regime. There is however a reduction in events above bankfull which will reduce the risk of triggering avulsions.

The Y30D30 flow option results in a similar impact score, although slightly higher than the Y45D30 result due to a lesser reduction in flows above bankfull.

6. Limitations and Constraints

This desktop assessment is based on limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Nanson, G. C., Knighton, D.A. 1996. Anabranching rivers: their cause, character and classification. Earth Surface Processes and Landforms. 21-3.

Erskine. W., Rutherford, I., Sherrard. J., Tilleard. J. 1993. *Investigation of River Channel Changes. River Murray and Anabranches between Hume Dam and Lake Mulwala*. Murray-Darling Basin Commission Report.

Sub-Reach 2 Geomorphic Outline – Howlong Reach

Figure 1 Sub-reach map extent

1. Reach position in catchment and general description

The Murray River is a "Type 3: *mixed-load, laterally active anabranching river*", (Nanson & Knighton, 1996). By definition, this means that the Murray River is characteristically a dynamic river system where:

- The meander bends are free to progress across the floodplain surface.
- Meander cut-offs are common (oxbow lakes).
- Multiple river channels can form, where a secondary channel leaves the parent river (in this case the Murray River) to re-join it further downstream (defined as an anabranch). Contemporary anabranches occur along almost the entire reach.

This description fits well to this sub-reach and the broader Albury, Howlong and Mulwala reaches.

The Little River anabranch complex (sub-reach 2) is situated on the NSW floodplain, comprising two channels, namely Little River and McLeans Creek. The sub reach is situated approximately 12 km downstream of Howlong. The Little River channel extends approximately 2.25km long. The corresponding section of the Murray River extends 4.86km.

The anabranch network represents a more hydraulically efficient flow path compared to the adjacent section of the Murray River.

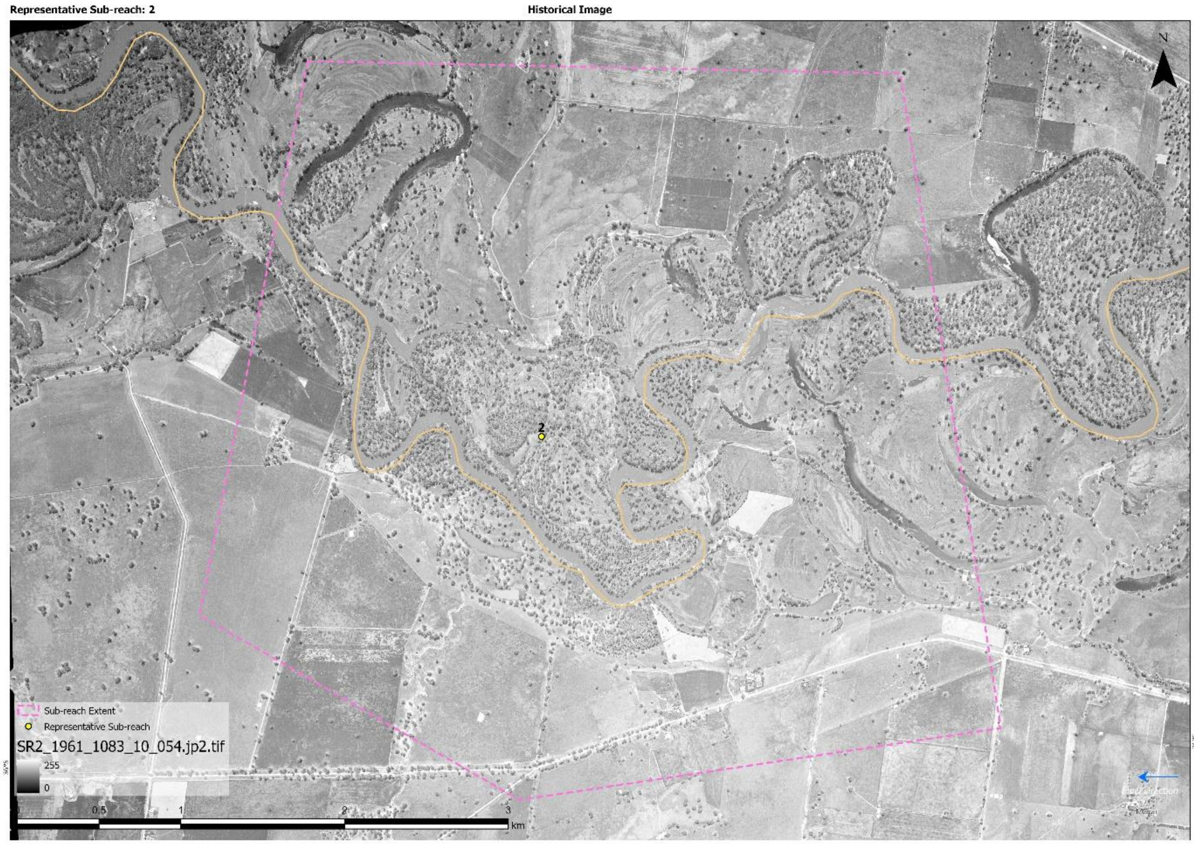

Figure 2 Historic imagery (circa 1961) of the sub-reach extent

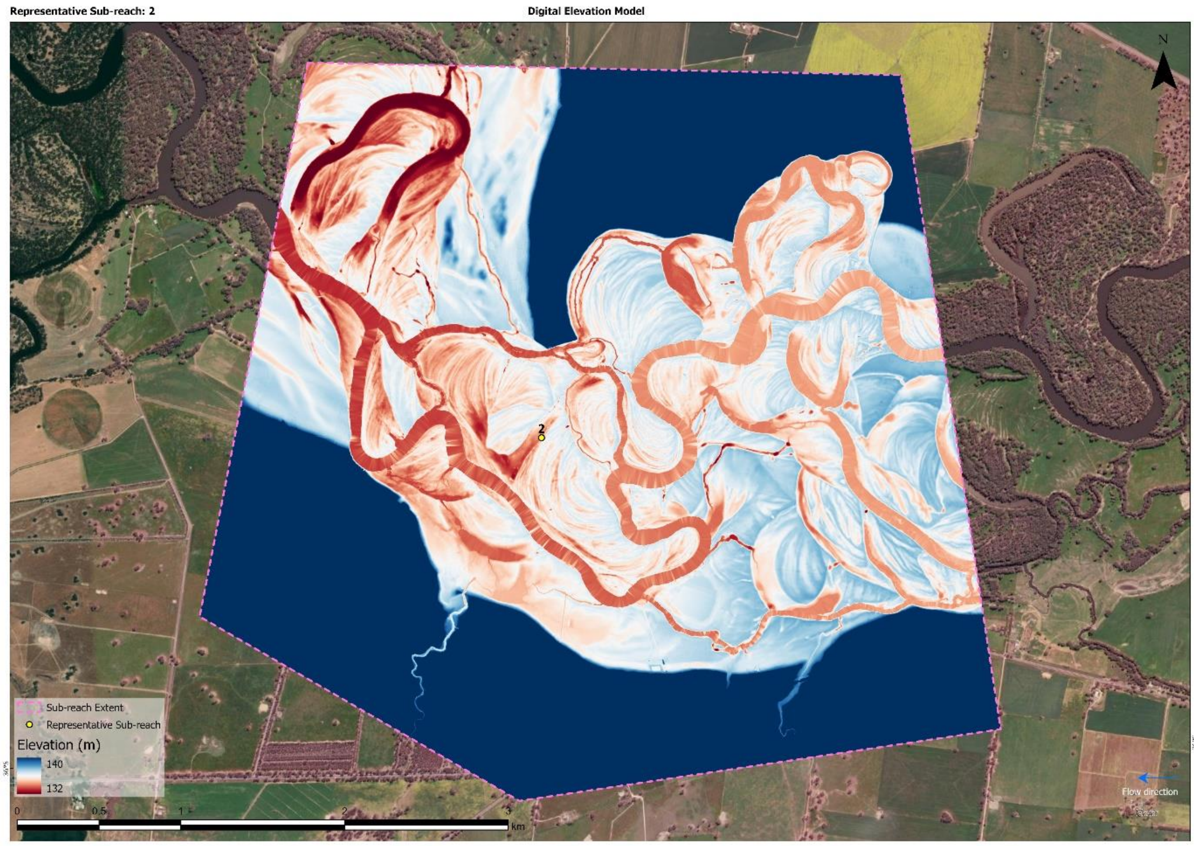

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

2. Channel form and processes

a. Anthropogenic Influences

Erskine *et al*. (1993) investigated channel changes on the Hume to Yarrawonga (Lake Mulwala) reach of the Murray River. They proposed that the changes having greatest influence on the physical form of the river were:

- River regulation. The extensive changes to the flow and sediment regime of the Murray River due to regulation is known to impact on the morphology of the river.
- Floods. Floods are recognized to be important agents of geomorphic change, especially the initiation and connection of anabranch channels. However, the presence of Lake Hume has influenced the frequency and duration of floods.
- De-snagging. De-snagging has contributed towards a loss of in-stream morphologic diversity in the Murray River in this sub reach. De-snagging has not been undertaken in the anabranches.
- Changes in riparian vegetation. The anabranch network is primarily located on freehold land and has been subject to unrestricted grazing pressures in the past.
- Boat waves. Boat waves are not a big influence within this reach.

b. Historic changes based on the historical imagery

A review of 1948 aerial photography found that the Little River and McLeans Creek channel position has largely remained the same. There are no obvious major changes in channel planform position. Primary processes occurring within the anabranch network are channel widening and bed aggradation. Of particular concern is an outside bend of the Murray River upstream of the Little River offtake. Progressive lateral migration of this bend has the potential to erode into the Little River channel, thus increasing the potential for channel expansion within Little River.

c. Forms (mainly based on LiDAR).

Little River has an approximate bank full width of between 30 and 40 metres and a depth estimated to be between 4 and 5 metres. Erskine et al. (1993) found that at a single cross-section in the lower half of Little River there has been a 10.6% reduction in channel depth between 1977 and 1992. This suggests there may be bed load deposition occurring within the downstream section of the anabranch.

d. Processes

The Little River anabranch system is significantly straighter, steeper and hence shorter than the adjacent section of the Murray River. Despite this, Little River does not appear to be actively developing. Progressive lateral migration of an upstream bend on the Murray River has the potential to erode into the Little River channel, thus increasing the potential for channel expansion within Little River.

3. Floodplain form and process

a. Anthropogenic changes

The anabranch network is primarily located on freehold land and has been subject to unrestricted grazing pressures in the past. A review of current and 1940's aerial photography shows that River Red Gum density has significantly improved since the 1940's.

b. Hydrological connections

The anabranch network is well developed and carries flow during both high and low regulated flow conditions. The anabranch network is also well connected to the surrounding floodplain surface and inset features including palaeochannels.

Bankfull channel capacity is around 25,000 ML/d, with several anabranches active. Floodplain inundation from 25,000 ML/d to 40,000 ML/d is confined to scroll bars and cut-off channel. Widespread floodplain inundation only occurs above 40,000 ML/d.

c. Form (mainly based on LiDAR)

The LiDAR data and aerial imagery shows a complex topographic floodplain surface, comprising palaeochannels, scroll bars and flood channels.

d. Processes

Palaeochannels are activated during sub bankfull flow events and greater. Flood channels are activated during bankfull flow events and greater. The development and evolution of anabranches involves the erosion and enlargement of a channel system, thus capturing flow from the parent channel.

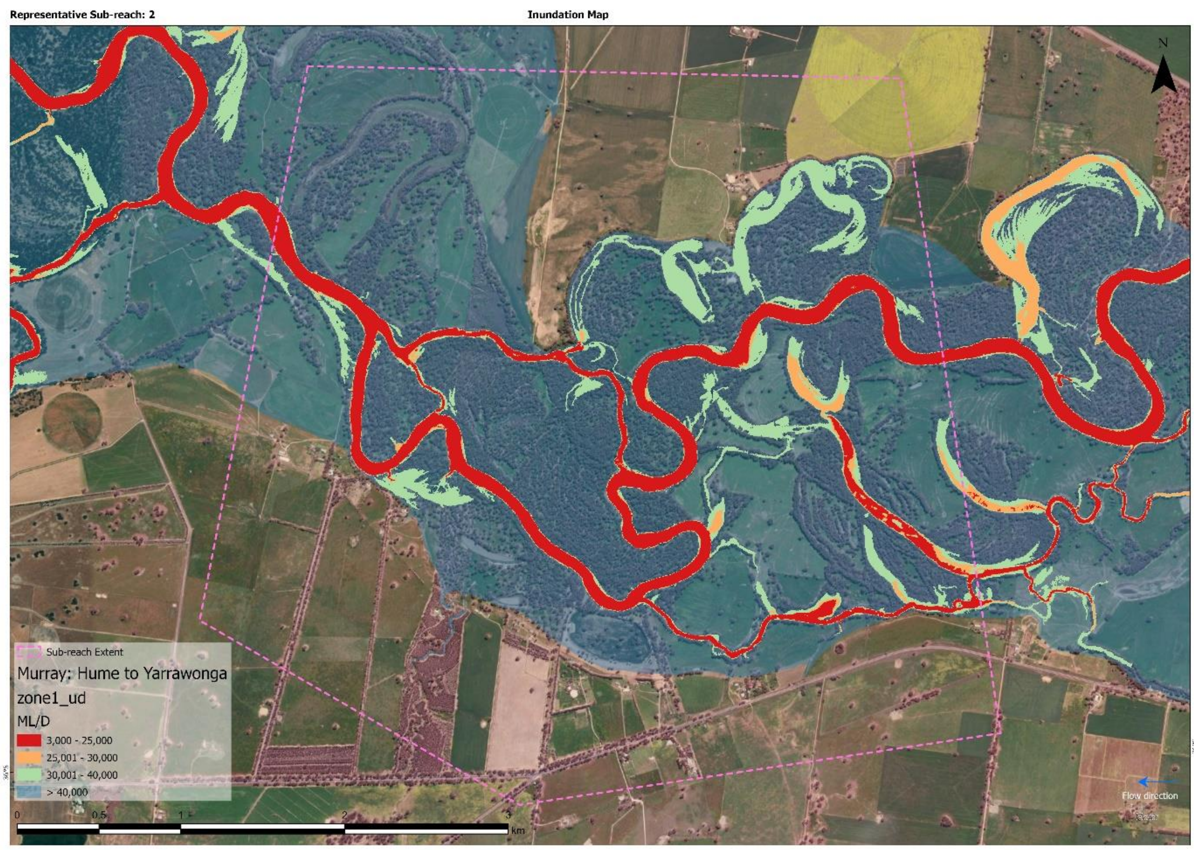

Figure 1 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic features and processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (sand slugs)	Aggradation
Floodplain (sub-bankfull - anabranch/floodrunners	Avulsion
Floodplain (>bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 2 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows:

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Hume to Yarrawonga	25,000 @ Doctors Point (current flow limit) 30,000 40,000	River Murray and floodplain from Hume Dam to Yarrawonga Weir (NSW and VIC sides)

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Sand Slugs	Aggradation / transport	1	2	2	2	2
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Floodplain (> bankfull)	Sediment desposition	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.01**	**0.82**	**0.39**	**0.22**	**0.08**
Likelihood (Y45D40 events per year)		1.00	0.87	0.67	0.19	0.07
Likelihood (Y30D30 events per year)		1.00	0.92	0.60	0.21	0.08

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.4	5.7	6%	5.7	7%
Sand Slugs	4.0	4.6	14%	4.6	15%
Anabranches / Floodrunners (sub-bankfull)	3.7	4.5	22%	4.5	22%
Anabranches / Floodrunners (> bankfull)	0.9	0.8	-16%	0.9	-3%
Floodplain (> bankfull)	0.9	0.8	-16%	0.9	-3%
Average	**3.0**	**3.3**	**8%**	**3.3**	**12%**

In its current form, both the Little River and McLeans Creek appear relatively stable (i.e., slow rates of change). Therefore, rapid channel development in both anabranches appears unlikely in the short term. Furthermore, there is evidence of bed aggradation within the downstream section of the Little River. Increases in bankfull flow and just above bankfull flow are not expected to cause rapid channel development in both anabranches but could increase the risk of such changes occurring.

The impact score for the sub-reach reflects the potential risks – under current constraints avulsions (through sub-bankfull anabranch development), continued aggradation and riverbank erosion have a similar impact score in terms of the link between the feature and flow regime (namely bankfull flows and above) and are more significant processes for this sub-reach than flood triggered avulsions or floodplain deposition.

For the flow options (Y45D40, Y30D30) the frequency of flows in the sub-bankfull and bankfull range is increased and so the risk of geomorphic processes more associated with these flows is increased.

The Y30D30 flow option results in limited change to flows above bankfull and so there is limited potential for changes in sediment deposition on the floodplain or new avulsion channel development which are associated more with these aspects of the flow regime.

6. Limitations and Constraints

This desktop assessment is based on limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Earth Tech (2008). Little River Reach River Management Plan. Earth Tech for NSW Department of Natural Resources, Albury NSW.

Erskine. W., Rutherford, I., Sherrard. J., Tilleard. J. 1993. *Investigation of River Channel Changes. River Murray and Anabranches between Hume Dam and Lake Mulwala*. Murray-Darling Basin Commission Report.

Nanson, G., Knighton, A. 1996. *Anabranching Rivers: Their Cause, Character and Classification*. Earth Surface Processes and Landforms, 21, 217-239.

Sub-Reach 3 Geomorphic Outline – Mulwala Reach

Figure 1 Sub-reach map extent

1. Reach position in catchment and general description

The Murray River is a "Type 3: *mixed-load, laterally active anabranching river*", (Nanson & Knighton, 1996). By definition, this means that the Murray River is characteristically a dynamic river system where:

- The meander bends are free to progress across the floodplain surface.
- Meander cut-offs are common (oxbow lakes).
- Multiple river channels can form, where a secondary channel leaves the parent river (in this case the Murray River) to re-join it further downstream (defined as an anabranch). Contemporary anabranches occur along almost the entire reach.

This description fits well to this sub-reach and the broader Albury, Howlong and Mulwala reaches.

The Boiling Downs Creek anabranch complex (sub-reach 3) is situated on the NSW floodplain, comprising Boiling Downs and Hans Creek. The sub reach is situated approximately 13km downstream of Corowa. Within the Hume to Yarrawonga reach, the Boiling Down Creek/Hans Creek anabranch is the shortest anabranch by comparison to its parallel main channel. The Boiling Down Creek/Hans Creek is 32.9% of main channel length (through the southern Snake Island neck cutoff) and the Hans Creek course is 38.7% of main channel length (Ian Drummond & Assoc., 1993). The longer course of Boiling Down Creek and Hans Creek around Snake Island is 46.8% of main channel length. Stream lengths of the primary anabranch network relative to the Murray River are provided in Table 1.

Table 1 Stream Length and Sinuosity Data (Ian Drummond & Associates, 1993).

Anabranch	Stream Length (km)	Sinuosity	Main Stream	Stream Length	Sinuosity
Boiling Down Creek/Hans Creek, Short Course	5.6	1.07	Murray River	17.0	2.16
Boiling Down Creek/Hans Creek, Long Course	8.1	1.10	Murray River	17.3	2.09
Hans Creek	4.1	1.10	Murray River	10.6	2.36

The anabranch network represents a more hydraulically efficient flow path compared to the adjacent section of the Murray River. The anabranch captures a considerable proportion of the flow away from the Murray River. Works aimed at managing anabranch development have been undertaken in Boling Down and Hans Creek.

2. Channel form and processes

a. Anthropogenic Influences

Erskine et al. (1993) investigated channel changes on the Hume to Yarrawonga (Lake Mulwala) reach of the Murray River. They proposed that the changes having greatest influence on the physical form of the river were:

- River regulation. The extensive changes to the flow and sediment regime of the Murray River due to regulation is known to impact on the morphology of the river.
- Floods. Floods are recognized to be important agents of geomorphic change, especially the initiation and connection of anabranch channels. However, the presence of Lake Hume has influenced the frequency and duration of floods.
- De-snagging. De-snagging has contributed towards a loss of in-stream morphologic diversity in the Murray River in this sub reach De-snagging has not been undertaken in the anabranches.
- Changes in riparian vegetation. The anabranch network is primarily located on freehold land and has been subject to unrestricted grazing pressures in the past.
- Boat waves. This section of the Murray River is subject to speed restrictions.

b. Historic changes based on the historical imagery

A review of 1941 aerial photography found that both Boiling Downs and Hans Creek channel position has largely remained the same. There are observable changes in channel width in several locations, particularly within Hans Creek. Primary processes occurring within the anabranch network are channel widening (likely occurring in at least part due to bed deepening) and lateral migration. The potential for further planform adjustment of Boiling Down Creek to the north is limited by the presence of the terrace, which is relatively more erosion resistant compared to the contemporary floodplain surface.

The anabranch network has been subject to active management over the last 20 years, including the installation of instream works in combination with fencing and revegetation aimed at managing anabranch development.

Figure 2 Historic imagery (circa 1963) of the sub-reach extent

c. Forms (mainly based on LiDAR)

Both Boiling Downs and Hans Creek exhibit a diverse range of longitudinal bed morphology, including riffles, pools, runs and bars. The adjoining section of the Murray River has limited in-channel geomorphic diversity due to the presence of sand slug.

d. Processes

The Boiling Down/Hans Creek anabranch system is significantly straighter, steeper and hence shorter than the adjacent section of the Murray River. As such, the anabranch system threatens to capture flow away from the Murray River. The creek is well developed and carries flow during both high and low regulated flow conditions.

3. Floodplain form and process

a. Anthropogenic changes

The anabranch network is primarily located on freehold land and has been subject to unrestricted grazing pressures in the past. A review of current and 1941 aerial photography shows that River Red Gum density has significantly improved since 1941.

b. Hydrological connections

The anabranch network is well developed and carries flow during both high and low regulated flow conditions. The anabranch network is also well connected to the surrounding floodplain surface and inset features including palaeochannels.

c. Form (mainly based on LiDAR)

The LiDAR data and aerial imagery shows a complex topographic floodplain surface, comprising palaeochannels, scroll bars and flood channels.

d. Processes

Palaeochannels are activated during sub bankfull flow events and greater. Flood channels are activated during bankfull flow events and greater. The development and evolution of anabranches involves the erosion and enlargement of a channel system, thus capturing flow from the parent channel.

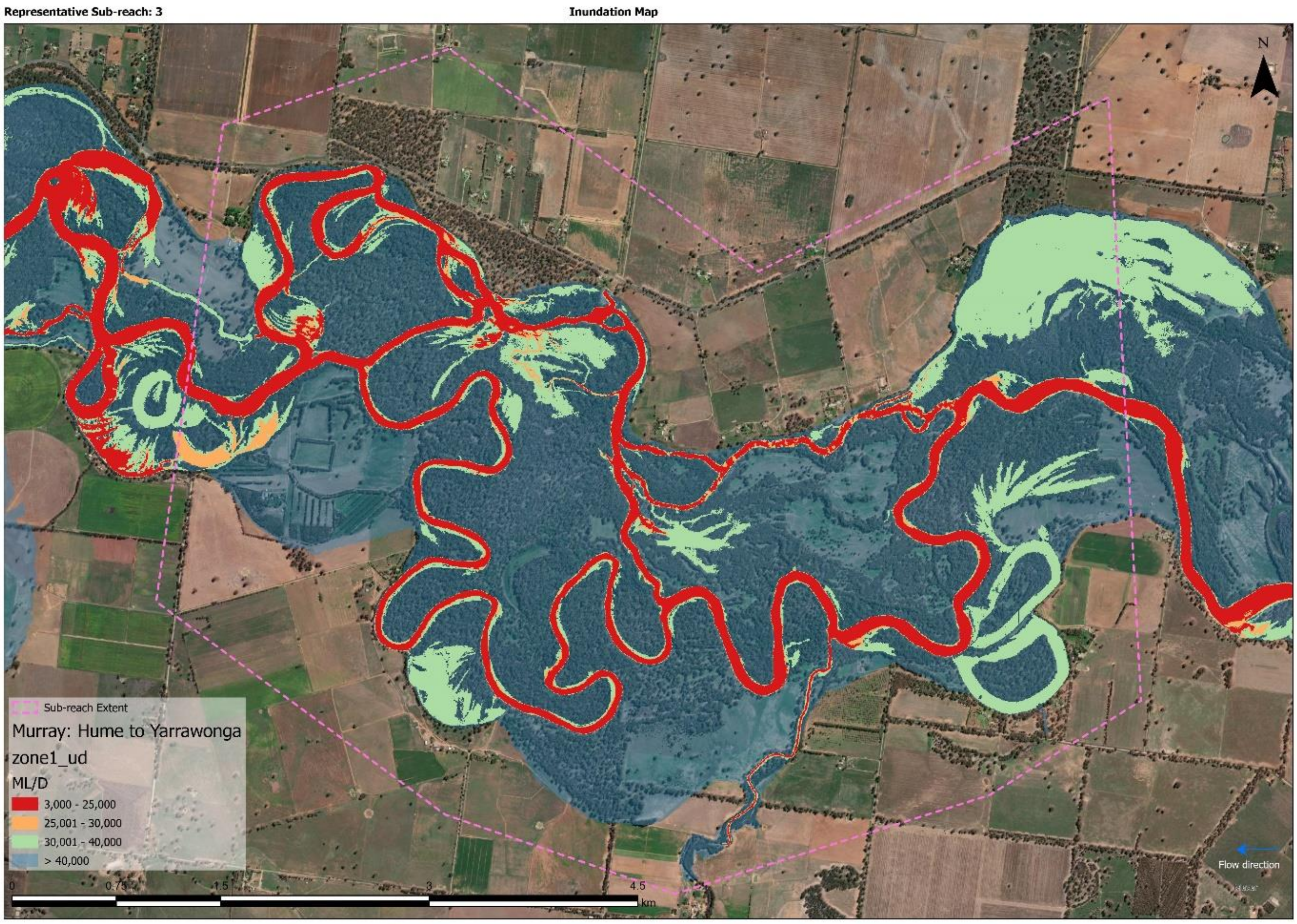

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

4. Base case

The base case geomorphic features and processes are summarised in Table 2.

Table 2 Geomorphic features and processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (sand slugs)	Aggradation / Sediment transport
Floodplain (cutoffs)	(avulsion / meander migration / meander extension)
Floodplain (sub-bankfull - anabranch/floodrunners	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 2 are summarised Table 4. The flow likelihood relates to the frequency of occurrence of the different flow categories

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows:

Table 3 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Hume to Yarrawonga	25,000 @ Doctors Point (current flow limit) 30,000 40,000	River Murray and floodplain from Hume Dam to Yarrawonga Weir (NSW and VIC sides)

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 4 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Sand Slugs	Aggradation / transport	1	2	2	2	2
Cutoffs	Avulsion / meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment desposition	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.01**	**0.82**	**0.39**	**0.22**	**0.08**
Likelihood (Y45D40 events per year)		1.00	0.87	0.67	0.19	0.07
Likelihood (Y30D30 events per year)		1.00	0.92	0.60	0.21	0.08

Table 5 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.4	5.7	6%	5.7	7%
Sand Slugs	4.0	4.6	14%	4.6	15%
Cutoffs	4.7	5.5	17%	5.5	17%
Anabranches / Floodrunners (sub-bankfull)	3.7	4.5	22%	4.5	22%
Floodplain (> bankfull)	0.9	0.8	-16%	0.9	-3%
Average	**3.7**	**4.2**	**11%**	**4.3**	**14%**

The current trajectory of the reach (channel and floodplain) is in terms of physical form is likely to be ongoing anabranch development of Hans Creek in particular. As such, the Boiling Downs/Hans Creek anabranch threatens to capture flow away from the Murray River. Increases in bankfull flows and above will enhance ongoing anabranch development of Hans Creek through the erosion and enlargement of the channel.

The impact score for the sub-reach reflects this potential risk – under current constraints cut-offs (avulsion / meander migration) and anabranch development have a high score in terms of the link between the feature and flow regime (namely bankfull flows and above). For the flow options (Y45D40, Y30D30) the frequency of flows particularly in the bankfull range is increased. An increase in the frequency of high freshes may also increase the risk of enhancing existing geomorphic processes such as bank erosion or aggradation of the bed in this reach, which is also a risk under the current constraints flow regime.

6. Limitations and Constraints

This desktop assessment is based on limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

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Sub-Reach 4 and 5 Geomorphic Outline – Barmah Reaches 1 and 2

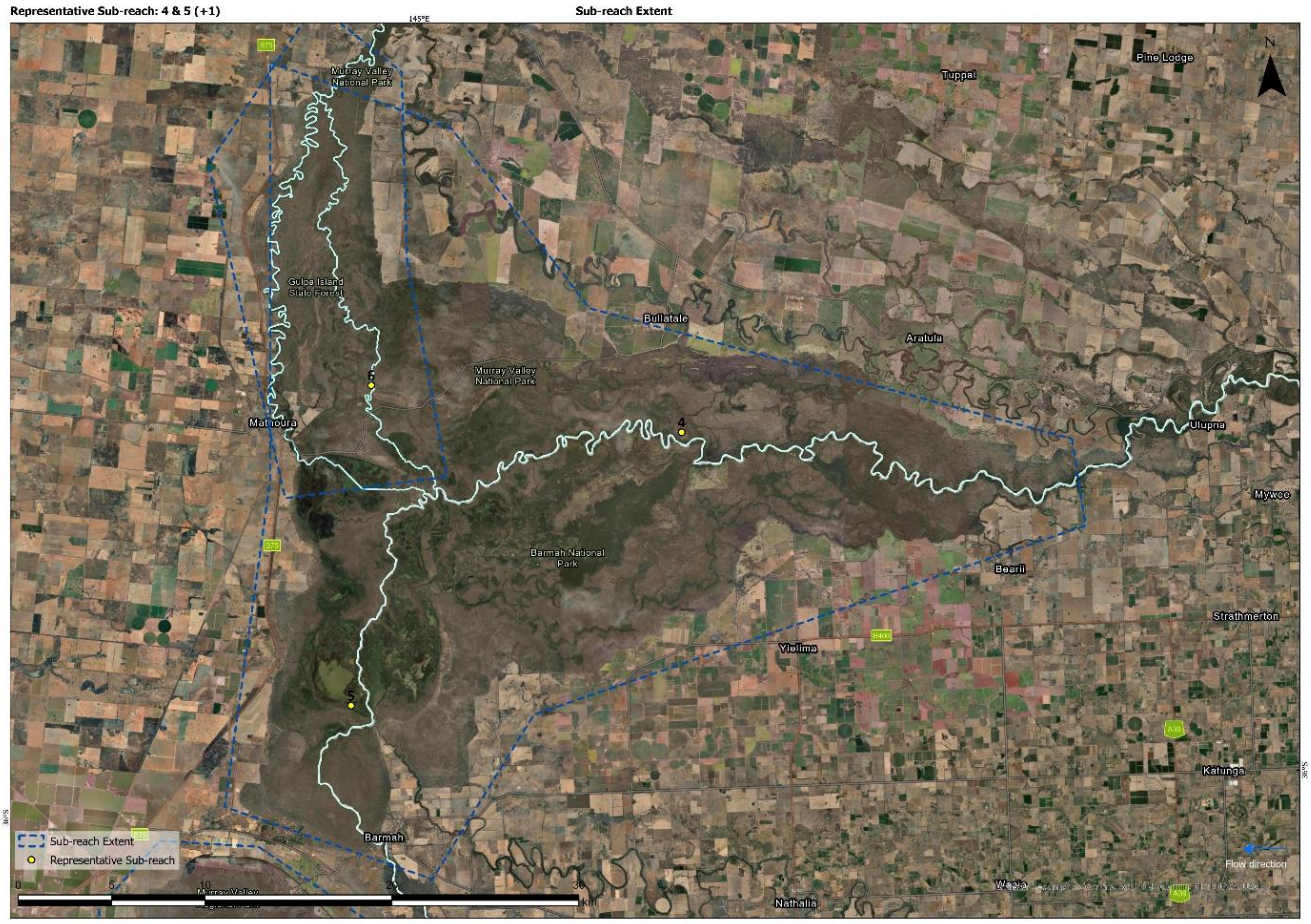

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

Sub-reach 4 is on the River Murray, and it extends from the Murray-Bullatale Creek junction to Picnic point at Edward-Murray junction. It includes a valley distance of approximately 134 km. It flows within the Barmah-Millewa Forest, the largest River Red Gum Forest in Australia. It belongs to a number of distributaries including Toupna Creek, Nine Panel Creek, Chimnew Creek and Edward River on NSW side and Gulf Creek and Sandpit Creek on Victoria side. It consists of a landscape of a broad flat floodplain interconnected through a network of floodplain channels, paleochannels and creeks. The Yarrawonga Weir (118 GL) plays a vital role in regulating flow of this reach. The flood hydrology of the reach is changed by the offtakes to Tuppal and Bulatale Creeks at the upstream end, and the Edward offtake at the downstream end.

Sub-reach 5 is immediate downstream of sub-reach 4, and it extends for a valley distance of approximately 58 km up to the Bama Sandhill. It runs through the renowned 'Barmah Choke', which is the greatest flow restriction section in the Murray River (MDBA, 2009). The reach occupies two big lakes: 1) Barmah Lake on Victoria side and 2) Moira Lake on NSW side.

Flooding pattern in the combined area of reach 4 and 5 is affected by a number of creeks and anabranching systems. During overbank events, majority of the Murray flow enters the Edward system and return to the River Murray downstream of Kyalite. Same but smaller scale of flow diversion happens on the Victoria side. A number of anabranching systems such as the Gulf Creek system divert water from reach 4 to the Southwest side and return to the Barmah Choke at reach 5. This kind of flooding pattern creates the Barmah Forest as a detention pondage (Currey & Dole, 1978).

2. Channel form and processes

a. Anthropogenic changes

Reach 4 and 5 is mainly regulated by the Yarrawonga Weir, which is approximately 230 km downstream of Lake Hume and 1,992 km downstream of the River Murray source. The weir has two channels: Mulwala canal, which serves the Edward River and Yarrawonga main channel, which serves the Murray main channel up to Barmah and south to the Broken Creek system. There are in total 28 regulators from Tocumwal to Torrumbarry Weir, of these only the regulators at the Gulpa Creek Offtake and Edward River Offtake remain active under regulated condition. During flood the Gulpa Creek, which diverts 350 ML/day under regulated conditions, is managed to divert the Murray flow (reach 4) up to 2000 ML/day to avoid unseasonal flooding in Barmah Forest (Thoms et al., 2000). Flows are limited to 18,000 ML/day at Tocumwal by Yarrawonga Weir to minimise downstream riparian flooding (MDBA, 2015).

b. Historic changes based on the historical imagery

Major change can be detected in the Barmah Choke section, which belongs to the reach 5. The channel in this section gets wider when comparison is made with 1945 aerial image. Noticeable change happens in the morphology of the levee channels in this period. The levee channels enlarge with some of them has established a clear joining path with the main channel. It implies future avulsion course in the system.

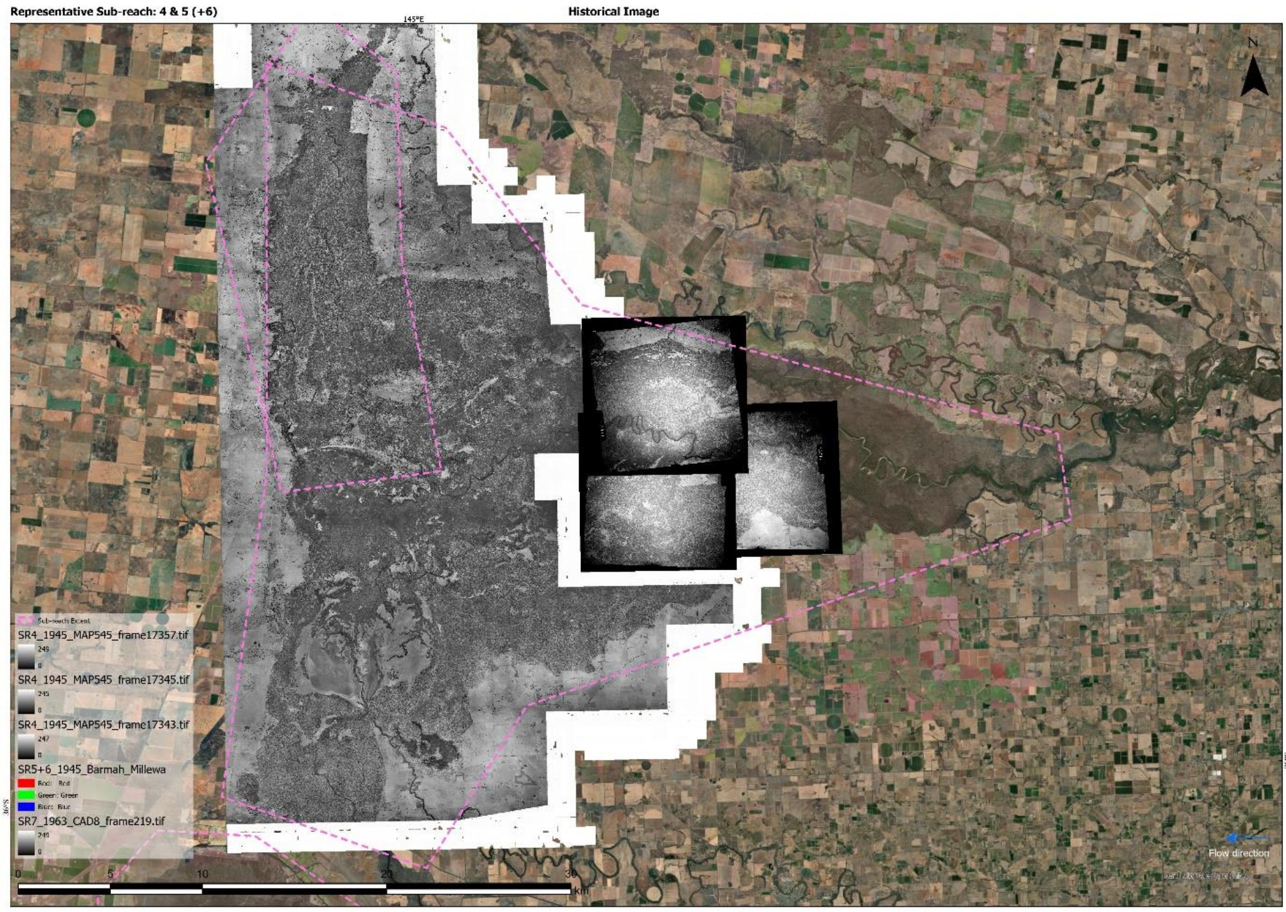

Figure 2 Historic imagery (circa 1945) of the sub-reach extent

c. Forms

Channel morphology of sub-reach 4 is remarkably different in bankfull width and depth than its immediate upstream reach extended up to Corowa. Where channel bankfull width ranges 90 to 210 m between Corowa and Bullatale Creek offtake, it ranges 50 to 160 m in reach 4. Bankfull depth between Corowa and Bullatale Creek offtake varies 5.5 to 10 m, but in reach 4 it varies 3.3 to 8 m (I. D. Rutherfurd & Kenyon, 2005). However, no change is observed in channel sinuosity between these two segments. The channel in sub-reach 4 is meandering with sinuosity of 1.4 to 2.3, with a median of 1.7.

The channel up to Barmah in sub-reach 5 is narrow and shallow compared to its upstream reaches (reach 4). It is because of the lunettes and prominent natural levees on the channel creating flow constriction. As per the technical report on Barmah Choke Channel Capacity studied by Water Techology (2020), recent channel width ranges approximately 80 to 50 m with a decreasing trend towards Barmah. Average channel depth also shows a decreasing trend with a range approximately 4 to 2 m at the choke. The channel leaving the choke towards the Bama Sandhill is wider and deeper than the channel from Picnic Point to Barmah. This occurs because all effluents except the Edward River return the Murray in this section. Channel width and depth in this portion vary 38 to 210 m and 4 to 10 m, respectively (I. D. Rutherfurd & Kenyon, 2005). Unlike to channel width and depth, sinuosity remains roughly same along the reach. The whole reach has fewer meanders with average sinuosity of 1.2 (Thoms et al., 2000).

d. Processes

Sub-reach 4 and 5 can be characterized by natural bank erosion though meander migration with the channel being broader with time. Erosion in these reaches is visible on both sides of the channel with straight planform sections, indicating the channel is broadening (Water Technology, 2020). On meandering planform sections, mainly in sub-reach 4, outside bends are the most common zones of erosion as identified by a survey of Forest NSW in 2008, which is documented in MDBA (2016) report. Slumping is the most usual erosion feature identified in these two reaches (Aquaterra, June 2013). Apart from slumping, notching is also present along both banks throughout these reaches, indicating the impact of flow regulation (Aquaterra, June 2013). Levee breakouts are very common geomorphic feature in these two reaches, resulting unseasonal flooding in the adjacent Ramsar-listed Barmah-Millewa Forest.

Sub- reach 4 and 5 have significant sediment storage, mainly coarse sand (20-200 µm) (Streamology, 2020) termed the ‘sand slug’. The upper section of the reach deposits bed sediment uniformly with developing regular dune-shaped bedform, whereas the narrower lower section deposits bed sediment in the scour pools with developing irregular bedform. Overall, the channel capacity in this reach is reduced by this sand slug. In case of sediment transport, there is a clear distinction between the upper and lower sections of the reach. It is observed that during a major flood year, the upper section can transport sediment more than 240,000 m^3, whereas the narrower lower section can transport only 80,000 m^3 (Streamology, 2020). This distinction is also true for non-flood year. As a consequence, sand aggrade the channel bed gradually, resulting in flow capacity reduction of the channel. It is also thought that the sand aggradation is increasing the rates of bank erosion and the formation of levee breakouts.

3. Floodplain form and process

a. Anthropogenic changes

As mentioned previously, there are 28 regulators in this site, of which 19 performs through the Millewa Forest on NSW side and remaining 9 performs through the Barmah Forest on Victoria side. The regulators at Edward River offtake and Gulpa Creek offtake are the only regulators that are kept active under regulated condition to meet irrigation demand at the adjacent catchment. Other regulators are opened under flooding time only, particularly when flow exceeds 10,600 ML/day at Tocumwal. As a consequence of this flow regulation, flood hydrology of the area has changed significantly.

b. Hydrological connections

The floodplain of both sub-reaches 4 and 5 is connected with the river by a number of effluents and influents. The major effluents of reach 4 includes Kynmer Creek, Sandpit Creek, Gulf Creek anabranching system, Punt Paddock Creek, Budgee Creek and Island Creek on the Victoria side. The floodplain on this side has intricate network of channel system joining one creek to another (e.g., Kynmer Creek joins the Gulf Creek system via Tullah Creek, Sandpit Creek and other unnamed creeks). Under high flow events a significant portion of the upper reach flow is diverted through this system and return to sub-reach 5 at Barmah.

The Toupna Creek, Morocco Channel, House Creek, Pinchgut Creek, Potts Creek, Nine Panel Creek, Nestrons Creek, Thistle Creek, Edward River, Gulpa Creek and Warrick Creek are the major effluents of sub-reach 4 on the NSW side. Until the Edward offtake, the Toupna Creek plays major role in connecting the floodplain with the River Murray since the creek receives flow from multiple creeks such as Thistle Creek and Nestrons Creek. The Edward River maintains its adjacent floodplain hydraulic connectivity throughout the year by receiving flow from the reach and Lake Mulwala via the Mulwala Canal.

Flooding characteristics of sub-reach 4 and 5 floodplain is spatially irregular. Flooding is comparatively frequent and spread out on the Victoria side than NSW side. Except few sections of both the reaches overtopping does not start at a flow of 11,000 ML/day at Tocumwal. Among these sections, the floodplains adjacent to the Barmah Choke and the Snag Creek-Tullah Creek are widely flooded. When flow ranges 31,000 to 40,000 ML/day at Tocumwal, the whole Barmah-Millewa Forest and its upstream Victorian floodplain adjacent to the intricate network of creeks led by the Gulf Creek get inundated. On the NSW side, flood is visible surrounding of the Toupna Creek system at this flow rate. The floodplain downstream of Barmah Choke is inundated at higher flow of more than 41,000 ML/day. Flow at 50,000 ML/day or more the whole floodplain adjacent to sub-reach 4 and 5 is inundated.

Reduced channel capacity (3 to 6% reduction) of the Barmah Choke (Streamology, 2020; Water Technology, 2020) and diverting flow by the Edward River play a key role in flooding in this site. It was recorded that a peak flow of 275,000 ML/day at Yarrawonga resulted in a peak flow of only 31,9000 ML/day at Barmah. Remaining of the flows passed through the Edward system.

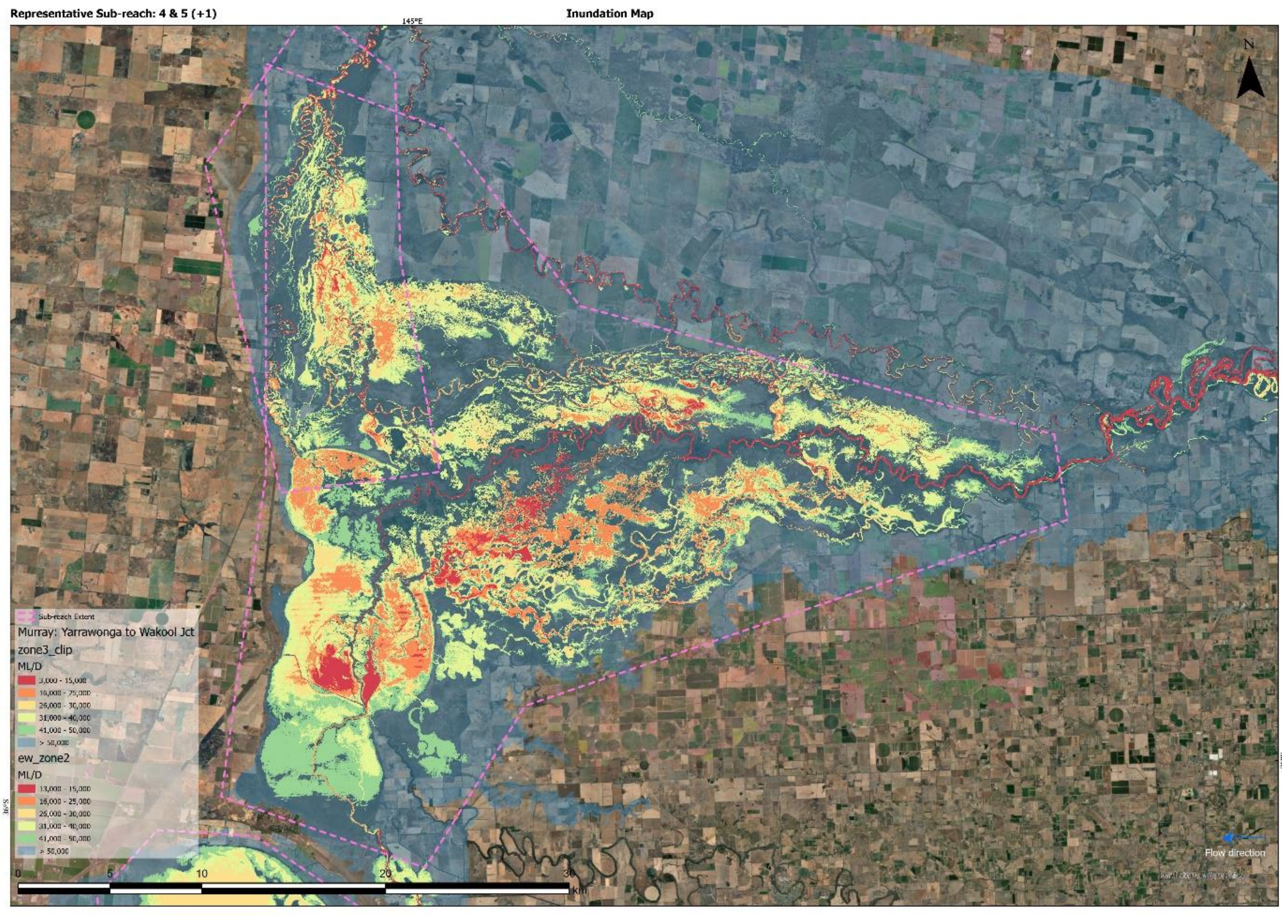

Figure 3 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

c. Form

The floodplain adjacent to sub-reach 4 is relatively unconfined than upstream floodplain. It is up to 30 km wide near Picnic Point as Rutherfurd (1994) indicated. However, downstream of the Picnic Point up to Bama Sandhill (reach 5) it is relatively confined with a width of approximately 10 km. Overall, the floodplain of both the reaches is characterized by vertical accretion dominating features that include crevasse splays, levees, levee channel, an intricate network of floodplain channels, flood runners and rill like channels. Except few sites (e.g., downstream of the Gulfa Creek offtake) the lateral accretion dominating features such as ridge, swales and meander cut-offs are not available on the floodplain.

d. Processes

The key process operating in the site floodplain development includes vertical accretion by an intricate network of floodplain channels and flood runners. Avulsion can also play an important role as the floodplain include paleo-channels at some points. However, from geomorphic genesis point of view the floodplain develops as a secondary product of the rise of the Cadell Fault Block, but primarily result of a series of avulsions (Rutherfurd & Kenyon, 2005).

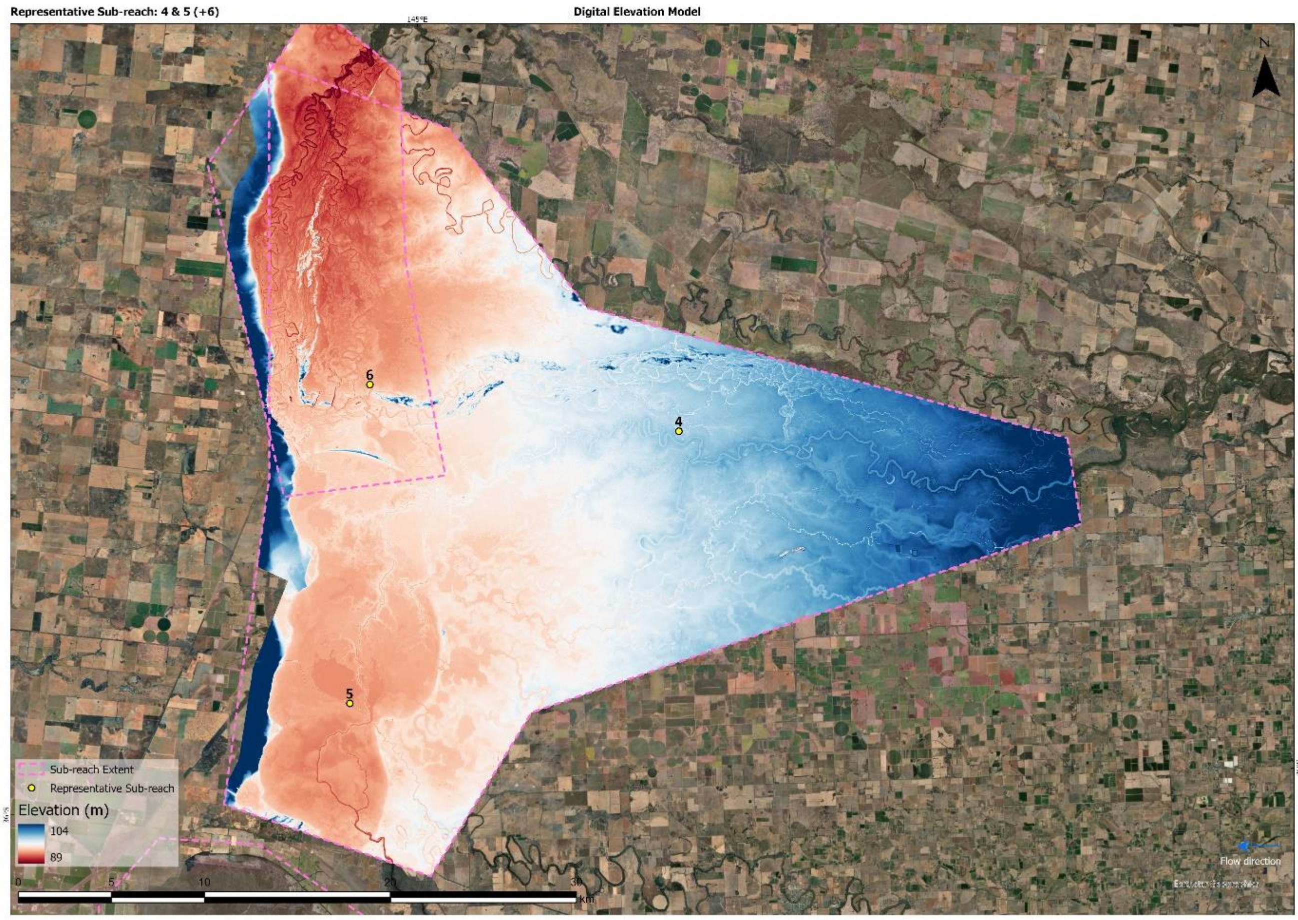

Figure 4 LiDAR DEM of the sub reach extent

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (bar)	Deposition
Channel (benches)	Deposition
Channel (sand slugs)	Deposition
Floodplain (levee)	Deposition
Floodplain (sub-bankfull – anabranch/flood runners/rill channels/ connected levee channels)	Most likely deposition but can create avulsion pathways
Floodplain (>bankfull – anabranch/flood runners/rill channels/ connected levee channels)	Deposition is replaced by erosion predominantly at the inlets with the main channel. Avulsion
Floodplain (>bankfull connection)	Deposition
Floodplain (wetlands, distributary systems)	Deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 4 and 5 are summarised Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows:

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Benches	Deposition	2	3	3	1	1
Bars	Deposition	1	2	3	3	3
Sand slug	Deposition	3	2	1	1	1
Capacity	Aggradation	3	2	1	1	1
Levee	Deposition	0	0	2	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.72**	**0.41**	**0.32**	**0.15**
Likelihood (Y45D40 events per year)		0.99	0.84	0.60	0.26	0.13
Likelihood (Y30D30 events per year)		0.99	0.84	0.40	0.29	0.14

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.3	5.6	6%	5.5	3%
Benches	5.9	6.7	14%	6.1	5%
Bars	5.1	5.6	11%	5.2	2%
Sand slug	5.3	5.6	6%	5.5	3%
Capacity	5.3	5.6	6%	5.5	3%
Levee	2.2	2.4	7%	2.1	-6%
Anabranches / Floodrunners (sub-bankfull)	4.1	4.7	14%	4.2	2%
Floodplain (> bankfull)	1.4	1.2	-16%	1.3	-7%
Anabranches / Floodrunners (> bankfull)	1.4	1.2	-16%	1.3	-7%
Wetlands, billabongs, distributary channels	2.6	3.0	13%	2.5	-6%
Average	**3.9**	**4.2**	**7%**	**3.9**	**1%**

Overall, the hydro-geomorphology of these two reaches is complex as it is a result of a complicated interactions of climate, tectonics, hydrology and sedimentology (Rutherfurd & Kenyon, 2005). Currently, aggradation processes dominate in channel, while floodplain process include deposition as well as floodrunner and avulsion development are occurring.

Bank erosion is an existing concern within these reaches, with evidence of increasing rates of erosion likely due to regulation, enhanced by boat wakes and the effect of the sand slug.

Loss of channel capacity is also a significant concern, with Streamology (2020, 2021) identifying an imbalance between the incoming sediment load and the ability of the system to transport sediment out of sub-reach 5. This has led to the significant build-up of sand within these reaches which is reducing the channel capacity and has the potential to continue to reduce capacity further. Streamology (2020) analysed sediment transport capacity through these reaches and found that flood events and bankfull flows are effective at transporting sediment, but the sediment transport capacity at the upstream of reach 4 is around four times the transport capacity at the downstream of reach 5. Flood events were also found to be effective at delivering sediment to the upstream of sub-reach 4, whereas regulated flows were most effective for transporting sediment through the reach.

Bank erosion, sediment aggradation and loss of capacity are significant geomorphic processes occurring under the base case conditions for sub-reaches 4 and 5 and indicated by their impact scores. The trajectory for the reach is for these processes to continue under current constraints, with the potential for an increase in the rate that these processes are occurring with an increase in high freshes and bankfull flows under the proposed flow options, particularly Y45D40.

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

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Sub-Reach 6 Geomorphic Outline – Upper Edward Reach

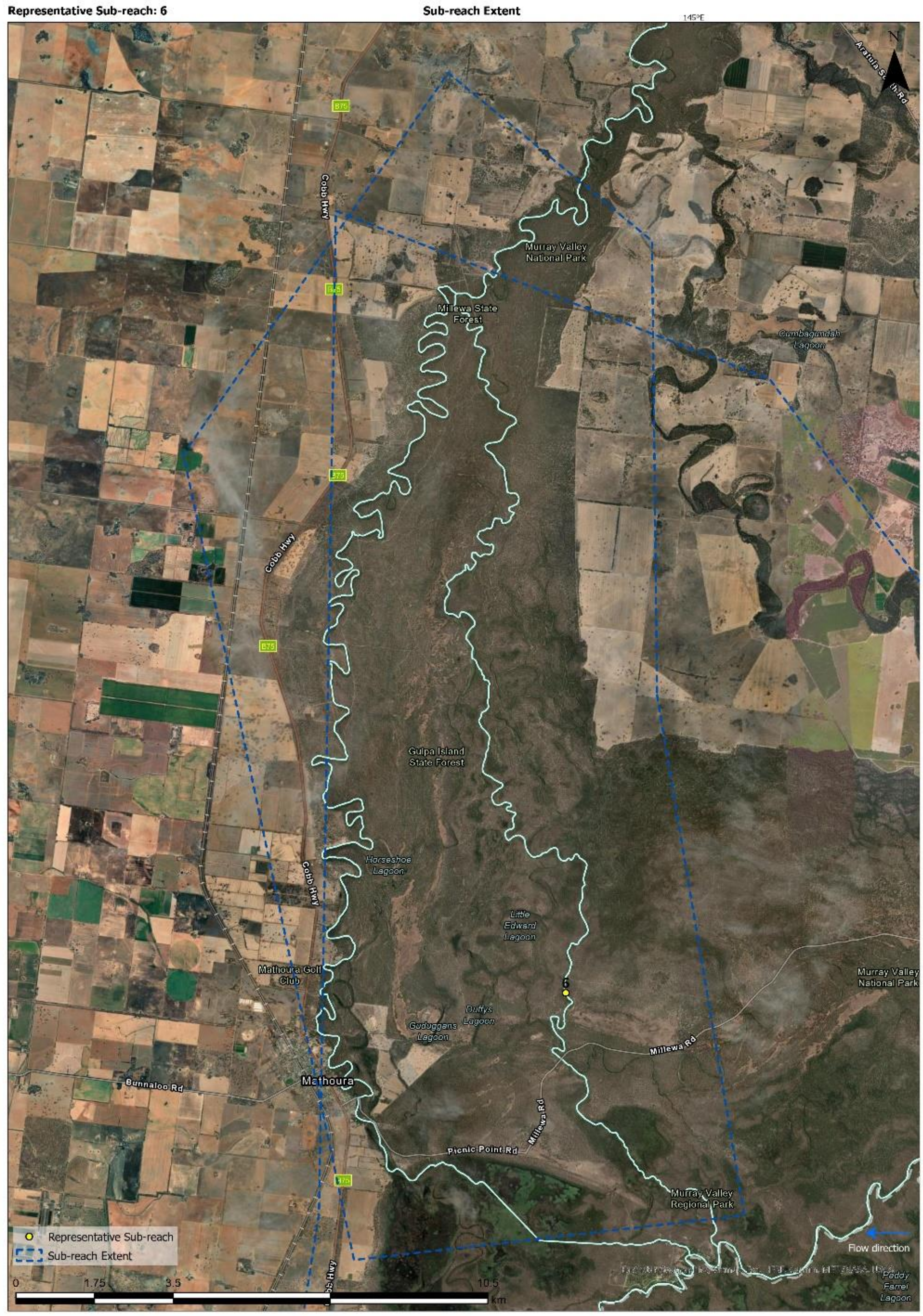

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

Sub-reach 6 consists of the Gulpa Creek and the upper section of the Edward River. It extends from the Edward-Murray junction at Picnic Point to the Edward-Gulpa Creek junction, and covers a reach length of approximately 80 km. The Edward River is the largest anabranch of the River Murray, flowing towards north up to Deniliquin and then Northwest to re-join the River Murray at Kenley. The site is characterised by a complex network of channels, permanent to intermittent and ephemeral creeks, flood runners, floodplain channels, levee channels, lagoons and wetlands. The Edward River and Gulpa Creek run actively under regulated condition in this system, whereas during high flow events these two run with a connectivity among many anabranches and the Barmah-Millewa Forest (Watts et al., 2020). The system as having a diversity of wetland and riverine habitats, has cultural, economic and environmental significance to the Murray region (Green, 2001).

2. Channel form and processes

a. Anthropogenic changes

The offtakes of both the Edward River and Gulpa Creek have regulatory structure that control flow with the River Murray system in order to meet the irrigation, environmental and social demands. Green (2001) mentioned that during peak irrigation period, this Edward-Gulpa system has to carry flow more than their capacity. As a consequence, overbank flooding becomes frequent in the Millewa Forest and connected wetlands, which in turn results in poor productivity of forest and wetlands.

b. Historic changes based on the historical imagery

The reach of the Edward River was changed with developing a number of wetland features and crevasse splays at its offtake. Apart from this, there were no observable changes in channel morphology and position in this reach between the 1945 black and white aerial photographs and the 2021 Maxar satellite imagery.

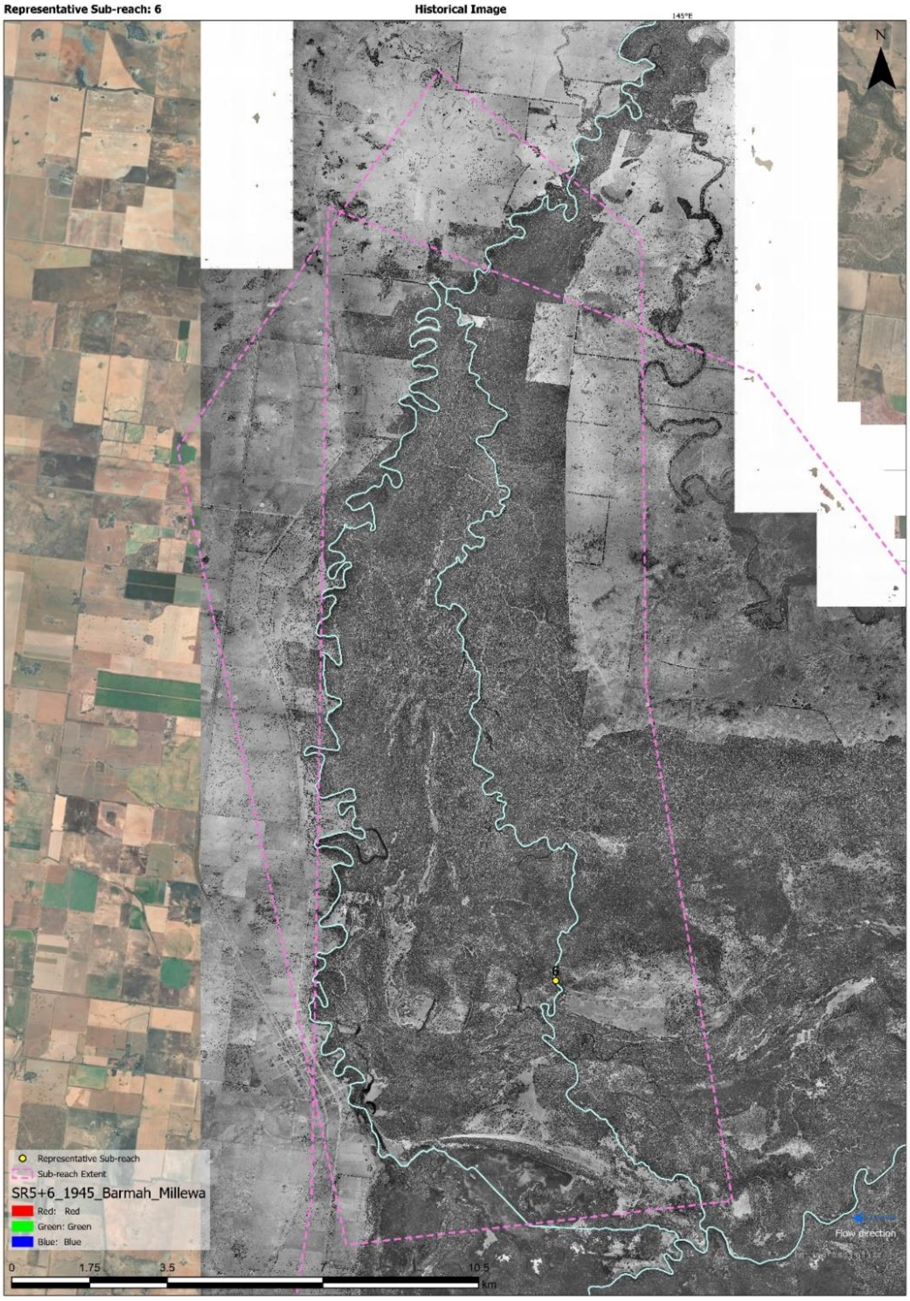

Figure 2 Historic imagery (circa 1945) of the sub-reach extent

c. Forms

The RiverStyles dataset developed by NSW government has described the section of the Edward River in this sub-reach as laterally unconfined, meandering to anabranching with a fine-grained channel bed. It would also be classed as 'distributary' in line with the broader Murray River system in this area. Sinuosity is low through this sub-reach of the Edward River except for the downstream section where it meets the Gulpa Creek. Gulpa Creek is described as laterally unconfined, meandering with a fine-grained channel bed all through the sub-reach. From LiDAR data it can be derived that the channel width of the Edward River in this sub-reach ranges approximately 25 to 65 m. The channel width decreases at the middle section where the river creates an intricate network of anabranching channels (distributary). Downstream of the sub-reach where a number of anabranches and floodplain channels re-join the main channel width increases noticeably. Sinuosity of the Edward River in this sub-reach increases slightly towards downstream from 1.4 to 1.9. Gulpa Creek has almost continuously maintained the channel width of approximately 35 m in this sub-reach. Overall sinuosity of the creek is very high compared to the Edward River. At some sections it is up to 3.4 whereas at other sections it is not less than 2.1.

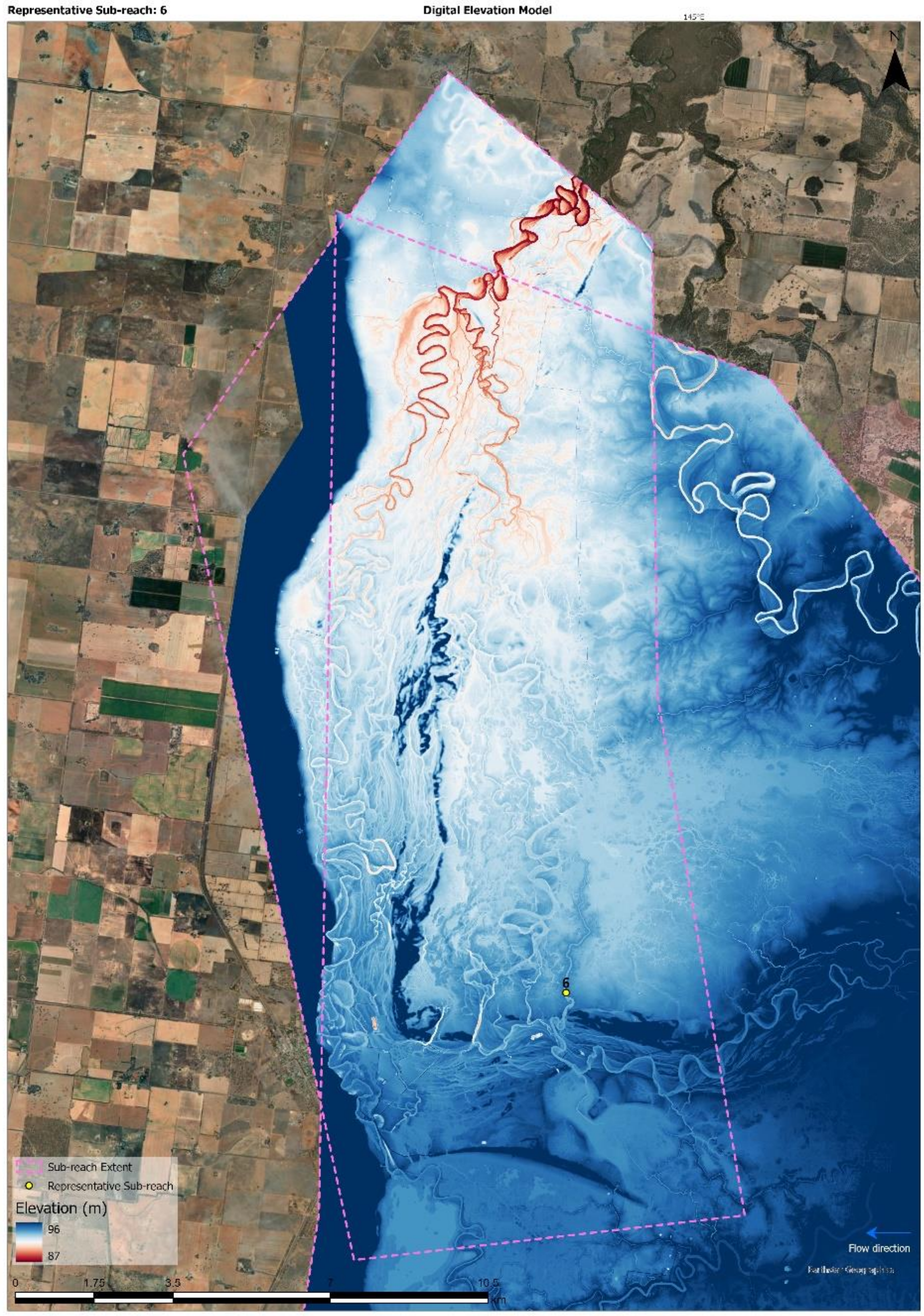

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

d. Processes

The channel in this sub-reach is affected by change in flow caused by regulation. Notching on the riverbanks is a typical outcome of flow regulation where water levels are maintained at a steady level for prolonged periods. Under unregulated flow condition during winter season, deposition may be occurring in this sub-reach if sand from the sand slug in the main River Murray channel is able to be transported through the regulator.

3. Floodplain form and process

e. Anthropogenic changes

The most significant anthropogenic change in this reach is the presence of the Edward River and Gulpa Creek offtakes from the River Murray which control much of the flow through this sub-reach.

There are no major changes such as roads or infrastructure to the floodplain section of the Edward River and Gulpa Creek in this sub-reach in recent times although much of the floodplain was managed through NSW Forestry until the 1990s. Land use change and changes in management practices have been significant anthropogenic changes on the floodplain.

f. Hydrological connections

The floodplain section in this sub-reach has a complex network of many anabranches and creeks, resulting a very high level of hydrologic connection with the main channel. Under flooding condition, some of the floodplain channels or creeks carry flow from the Edward River and result in floodplain inundation in the area, many carry flow from upstream of the Edward offtake on the River Murray. This high level of floodplain connection with both the Edward and River Murray creates very regular flooding in this area, which depends on the flow and volume of water downstream of Tocumwal and also the water level downstream of the Barmah Choke on the River Murray (Green, 2001).

There is a clear spatial variation in inundation between the floodplains of Edward River and Gulpa Creek. Until these two joins at down-valley, a vast area of the floodplain adjacent to the Edward River is inundated in contrast to the floodplain adjacent to the Gulpa Creek, and it happens when flow at Tocumwal is 40,000 ML/day or above.

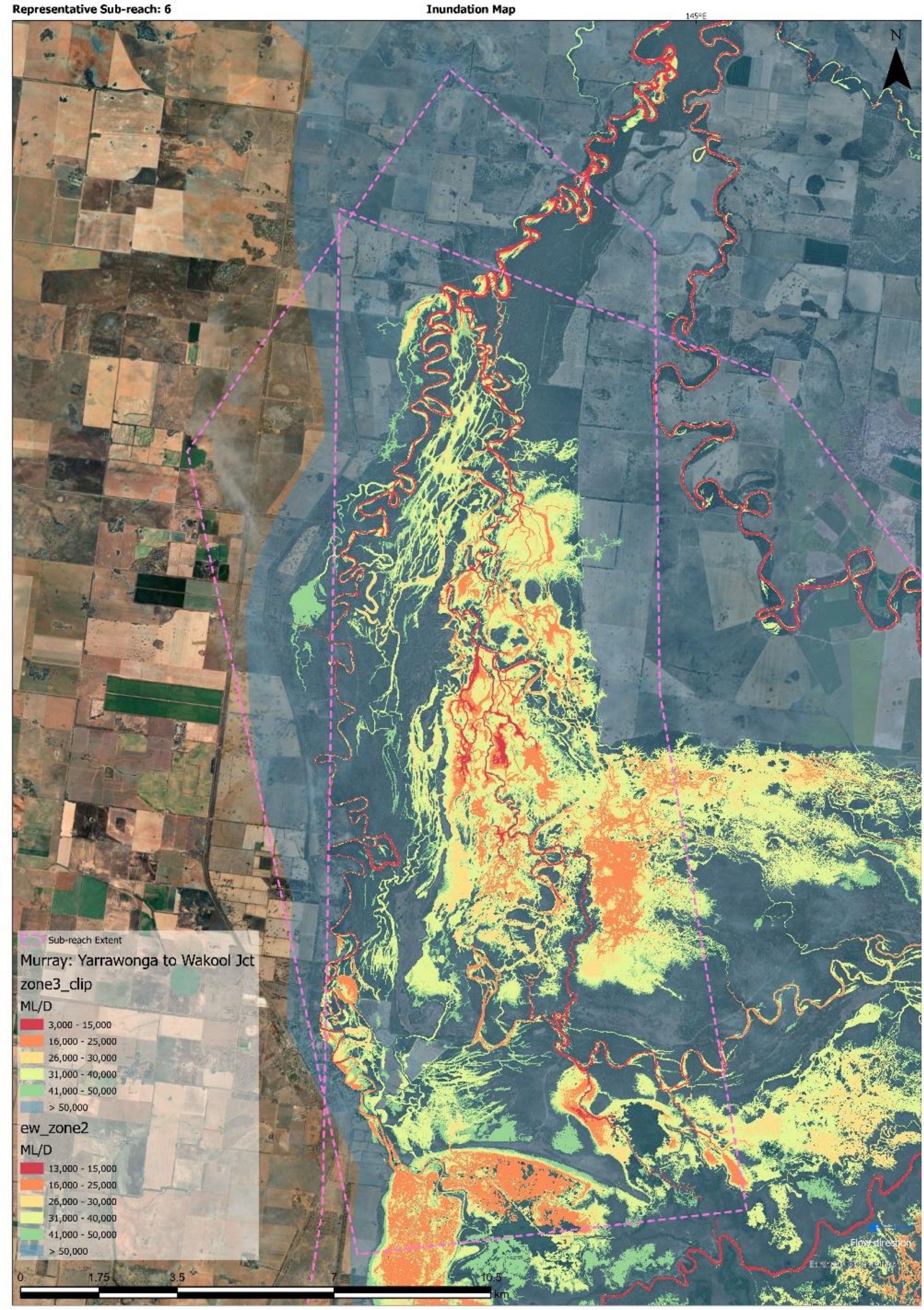

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

g. Form (mainly based on LiDAR)

From the geomorphic genesis point of view the floodplain in this section of the reach developed from the distributary fan of the River Murray at Tocumwal and is bounded by the Cadell Fault block that lies on the west of the Edward-Gulpa Creek system. The floodplain is approximately 6 km wide, occupying many channels and creeks of different character. The sub-reach also includes flood runners, creeks, meander cutoffs, paleochannels and wetlands. As delineated from LiDAR data (Figure 5), the western extent of the floodplain is bounded by the Cadell Fault block whereas the eastern edge is by the Bullatale Creek floodplain.

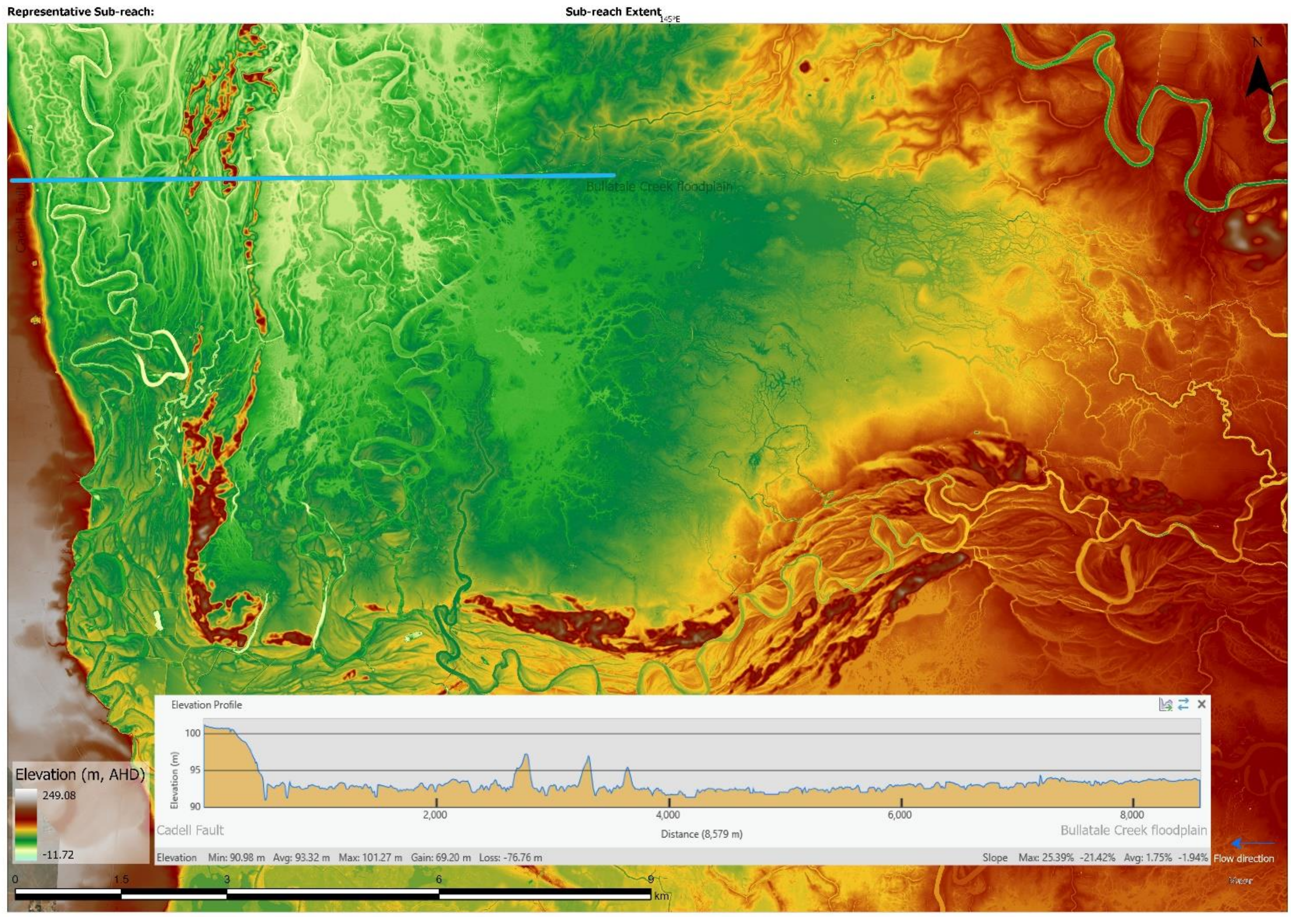

Figure 5. Exmaple of a typical cross-section profile for the sub-reach- 6 (taken from location of blue line on the figure)

h. Processes

The hydro-geomorphic process of the floodplain is balanced by both erosion and deposition under regulated conditions. Lateral erosion is a dominant process through meander cut-offs of the main channel. Vertical accretion on the floodplain is also important through crevasse-splays and overbank deposits (e.g., natural levees). Levee break outs are commonly visible along the channel, and they play a significant role in floodplain aggradation when the channels are at sub-bankfull flow levels.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (bar)	Deposition
Channel (benches)	Deposition
Floodplain (levee)	Deposition
Floodplain (sub-bankfull – anabranch/flood runners/levee channels)	Avulsion
Floodplain (>bankfull – anabranch/flood runners/levee channels)	Avulsion
Floodplain (> bankfull- potential avulsion channel)	Avulsion by both deposition and erosion.
Floodplain (>bankfull connection)	Deposition

Geomorphic Feature	Process
Floodplain (wetland, distributary)	Deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 4 and 5 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows:

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Benches	Deposition	2	3	3	1	1
Bars	Deposition	1	2	3	3	3
Levee	Deposition	0	0	2	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**0.98**	**0.69**	**0.49**	**0.29**	**0.16**
Likelihood (Y45D40 events per year)		0.99	0.85	0.66	0.26	0.15
Likelihood (Y30D30 events per year)		0.98	0.85	0.46	0.28	0.15

Table 5 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.3	5.7	9%	5.5	5%
Benches	5.9	6.9	16%	6.3	6%
Bars	5.2	5.9	13%	5.4	3%
Levee	2.3	2.5	8%	2.2	-5%
Anabranches / Floodrunners (sub-bankfull)	4.2	4.9	16%	4.4	4%
Floodplain (> bankfull)	1.4	1.2	-11%	1.3	-5%
Anabranches / Floodrunners (> bankfull)	1.4	1.2	-11%	1.3	-5%
Wetlands, billabongs, distributary channels	2.8	3.2	13%	2.7	-5%
Average	**3.6**	**3.9**	**11%**	**3.6**	**2%**

Riverbank erosion because of notching due to prolonged regulated flow conditions occurs throughout the Edward River system. Although this problem has been identified by Watts et al. 2020 for the lower reaches of the river, it is also likely to be occurring in this reach as identified by limited bank drone surveys in this sub-reach in 2019. This is evident in the impact score under current constraint, which is highest for bank erosion.

Large scale processes such as avulsion can also occur in this sub-reach due to the distributary nature of the waterway system and there are several potential avulsion paths visible from LiDAR, as shown **Error! Reference source not found.**. The path marked by blue colour is the current channel and by yellow colour is the potential avulsion course.

It is currently unknown as to whether the sand slug in the River Murray upstream of this sub-reach is affecting this sub-reach as well.

The frequency of the different flow categories under the flow options scenarios has adopted the available data for the River Murray downstream of Yarrawonga. The trajectory for the reach is for existing processes such as bank erosion to continue under current constraints, with the potential for an increase in the rate that other geomorphic processes such as anabranches development are occurring with an increase in sub-bankfull high freshes and bankfull flows under the proposed flow options, particularly Y45D40. The rate of change in geomorphic processes in this reach will be closely linked to how flow into the sub-reach from the Edward River and Gulpa Creek offtakes is managed.

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Baky, M. A. A. (2018). *Floodplain avulsion channels: understanding their distribution and how they reconnect to the parent channel.*

Bowler, J. M. (1978). *Quaternary climate and tectonics in the evolution of the Riverine Plain, southeastern Australia*.

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Rutherfurd, I. (1994). Inherited controls on the form of a large, low energy river: the Murray River, Australia. *Variability of Large Alluvial Rivers. ASCE, New York*, 177-197.

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Watts, R., Bond, N., Healy, S., Liu, X., McCasker, N., Siebers, A., . . . Vietz, G. (2020). Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project: Edward/Kolety-Wakool River System Selected Area Technical Report, 2019-20. *Report prepared for Commonwealth Environmental Water Office. Commonwealth of Australia*.

Sub-Reach 7 Geomorphic Outline – Echuca Reach

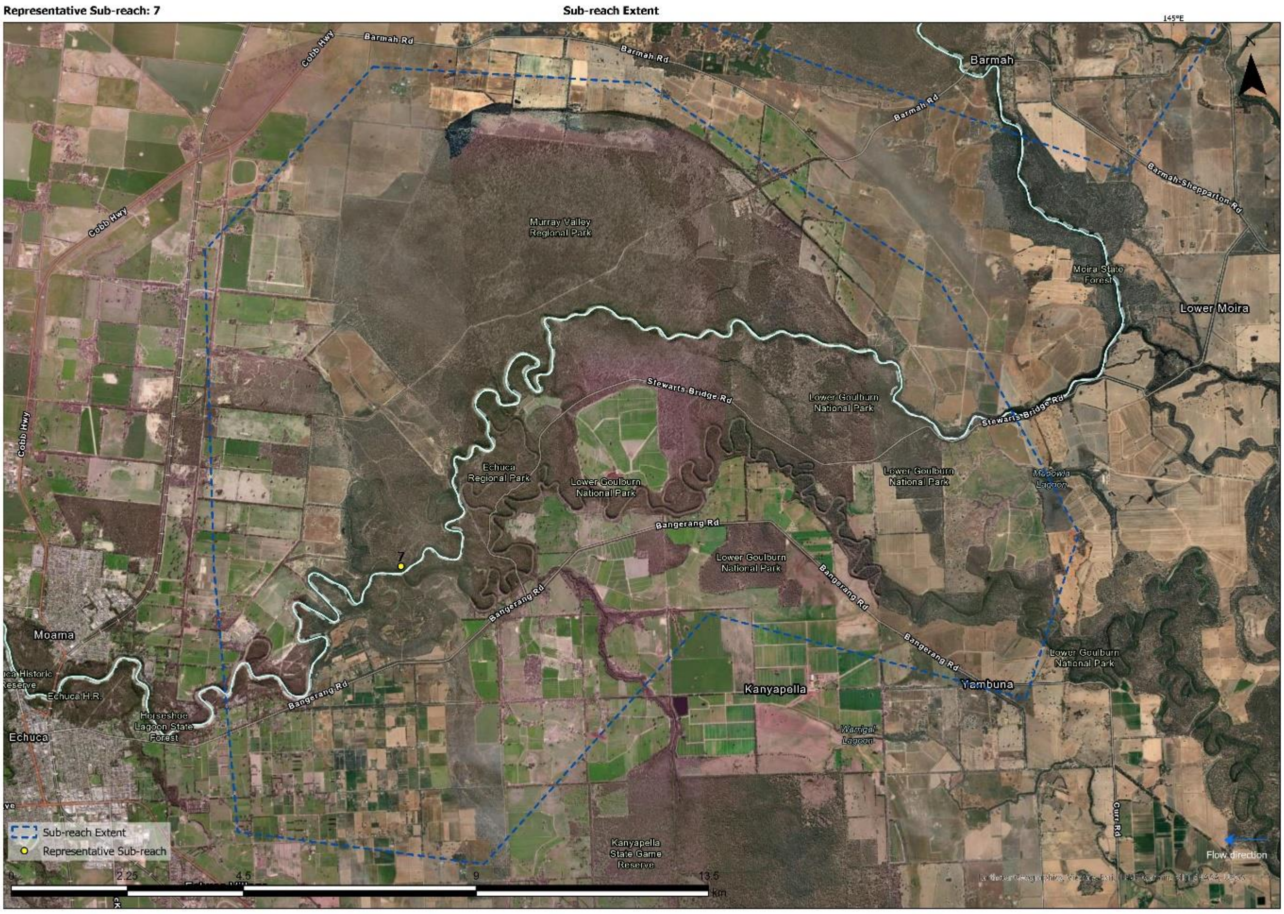

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The sub-reach is on the River Murray within the Kanyapella paleo-lake downstream of the Bama Sandhill, and the reach extends for a valley distance of 17 km. It is downstream of the main tributaries of the Ovens River and upstream of the Campaspe River. The river in this reach joins the Ancestral Goulburn Tract. Flows are regulated upstream by Dartmouth Dam (3,856 GL), Hume Dam (3,005 GL), Yarrawonga Weir (118 GL), Lake Eildon (3,334 GL) (Hale and SKM, 2011), and Goulburn Weir (25 GL).

The upstream section of the sub-reach is deflected by a late Pleistocene gravel fan (Stone, 2006a). The reach maintains a very narrow channel belt while continuing across the floor of the Lake Kanyapella but changes abruptly with the development of meander-belts and scroll bars when enters in the Kotupna paleochannel system (Rutherfurd and Kenyon, 2005; Stone, 2006a).

Both under natural and regulated conditions overbank events, the site is regularly flooded during Lower Goulburn River flood events and sometimes when the River Murray upstream experiences large floods. When floods occurs concurrently in the Murray and Goulburn systems, scouring along the sub-reach at the outer bends becomes common (Stone, 2006a). Nevertheless, the influence of Lower Goulburn River floods on the sub-reach is greater than River Murray floods, with backflows (reversed flow direction) occurring in the River Murray flow as a result of a backwater effect from high flows in the Goulburn River (Currey and Dole, 1978). The sub-reach adjusts with the increased discharge of the Goulburn River through its morphology within the Kotupna complex and further avulsions downstream (Stone, 2006a). This morphology includes many paleochannels, creeks and developing avulsion channels within its floodplain. The most notable of these is Backwater creek located on the NSW side of the river.

2. Channel form and processes

a. Anthropogenic changes

Although it is unknown when and at what extent the reach was desnagged, the River Murray between Albury and Echuca was generally desnagged between 1864 and 1869 with the removal of more than 3,000 large snags (Rutherfurd et al., 2020). Flow characteristics in this reach are associated with operations at Goulburn Weir and Eildon Dam (Maheshwari et al., 1995). Built between 1887 and 1891, the Goulburn Weir naturally diverts water along the Stuart Murray Canal, Cattanach Canal and the East Goulburn Main Channel. Lake Eildon Dam is located upstream of the Goulburn Weir. The dam was built between 1915 and 1929, and then modified in 1929 -1935 with increased storage capacity (377 GL). Further works to expand the capacity were then undertaken and by operation in 1956 it had a storage capacity of 3,3334 GL.

b. Historic changes based on the historical imagery

No large-scale changes have occurred except for the changing meandering wavelength, amplitude and radius of curvature at several bends in the Kotupna Complex.

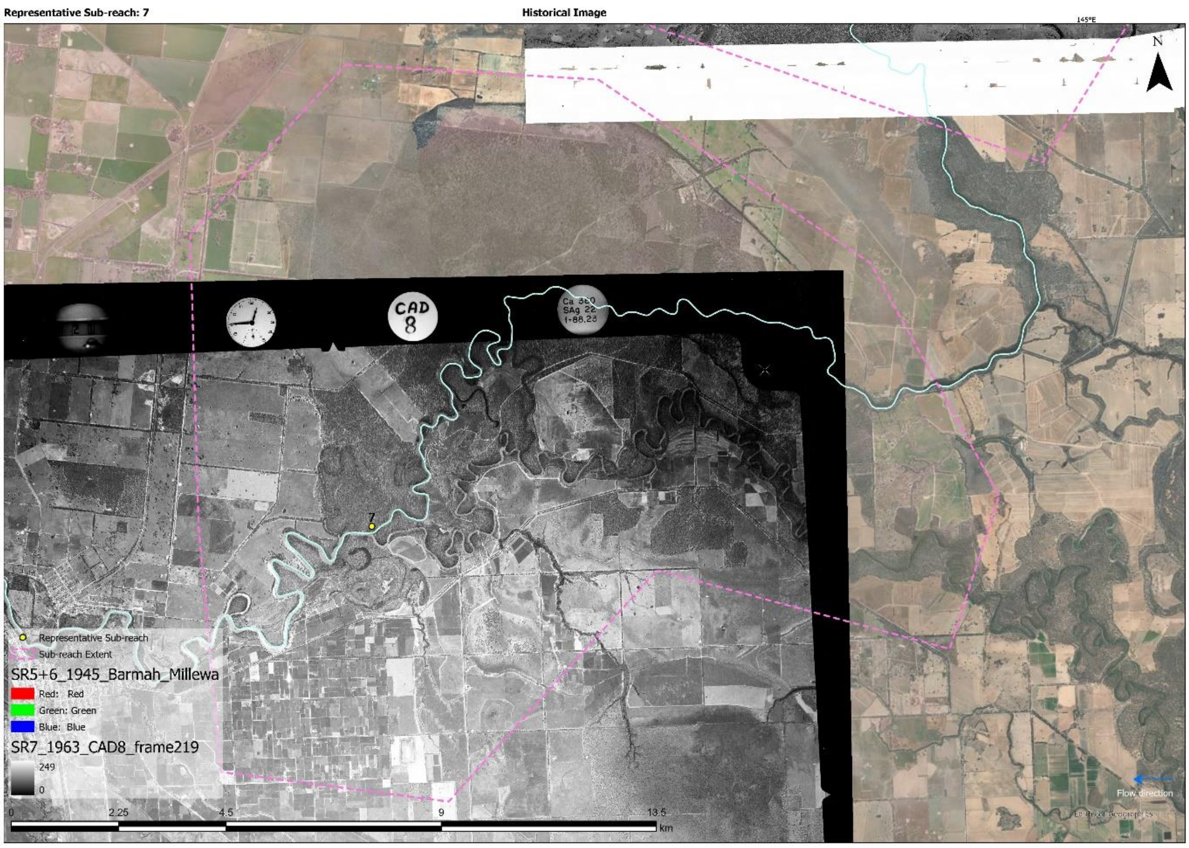

Figure 2 Historic imagery (circa 1945) of the sub-reach extent

c. Forms

The channel is meandering in form with increasing sinuosity downstream from the River Murray junction with the Goulburn River. The sinuosity upstream of the junction is 1.6, which increases to 2.2 as the channel nears the Goulburn River (Rutherfurd, 1994). The floodplain in this area is up to 10 km in width. The natural levee on the banks in this area is not as prominent as through the Barmah reaches upstream.

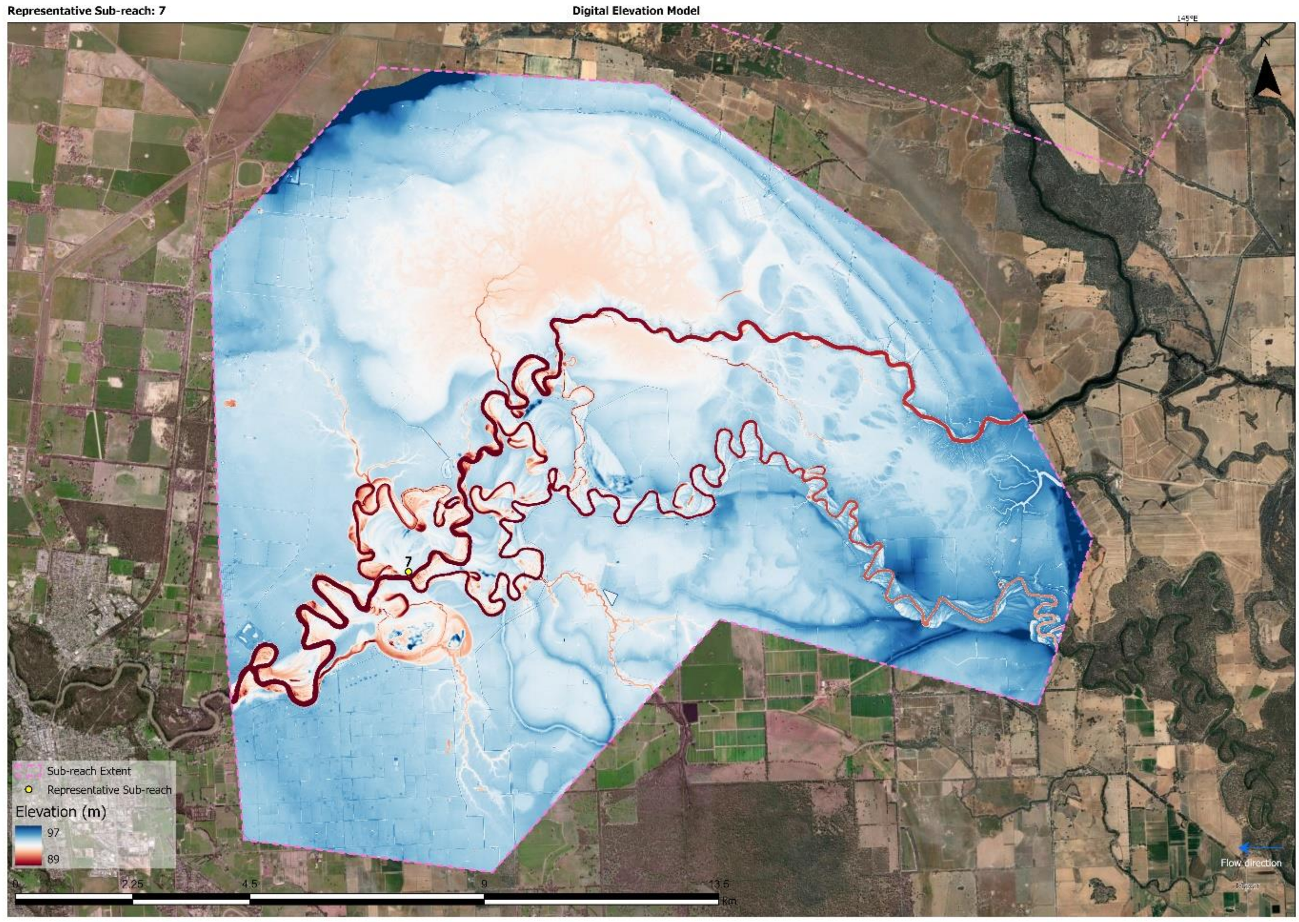

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

d. Processes

In this area, the dominant riverbank sediments are fine to medium silty clay as found by Baky (2018), which is supported by Stone (2006b) and Bowler (1978). Erosion is the dominant in-channel process, and has been occurring from when the channel developed by cutting through the floor of Lake Kanyapella (Rutherfurd and Kenyon, 2005). The modern channel is still experiencing erosion, the rate of which is being enhanced by boat wash from recreational vessels. Partial cross sections surveys conducted by Soil Conservation Services suggests that where boat usage is high the upper riverbank area on the outside of bends is accelerated compared to bends where there are fewer boats. This enhanced erosion decreases significantly with decreasing boat usage and between outer and inner banks.

3. Floodplain form and process

e. Anthropogenic changes

Apart from land use change, anthropogenic changes are minimal across the sub-reach. There are several water channel/ pipes in the upstream and downstream sections of the sub-reach, and all of them are at NSW side.

f. Hydrological connections

Until the junction with Lower Goulburn River, the floodplain does not include any major inflow or outflow points. There are some crevasse-splay channels immediate downstream of the Bama Sand hill, and further downstream there are two noticeable floodplain channels (potentially head-cut developing avulsion channels) on Victoria side (Baky, 2018). On the NSW side, there are series of crevasse-splay channels with significant levee breakpoints of different sizes. A major inflow occurs via Deep Creek into the floodplain on NSW side. When flood occurs, this creek plays a vital role in inundating the Kanyapella paleo-lake (i.e., Murray Valley Regional Park) on NSW side.

There are several paleochannels and oxbow lagoons within the Kotupna complex, the meeting place between the River Murray and the Goulburn River. The distribution of major floods in this area suggests that the Goulburn River has been the dominant driver in hydrologically connecting these features. It was recorded that the Goulburn River with a peak flow of 104,000 ML/day resulted in only a peak flow of 100, 000 ML/day at Echuca. In fact, the full River Murray flow does not come into this Kanyapella system as flows is also diverted into the Edward-Wakool system upstream and during large flood events a significant proprition of the flow from the River Murray flows north around the Barmah-Millewa reach. For instance, a recorded peak flow of 275,000 ML/day at Yarrawonga resulted in only a peak flow of only 31, 900 ML/day at Barmah (Currey and Dole, 1978). It is estimated that the Kanyapella paleo-lake on the NSW side is completely inundated when flow at Barmah point is around 30,000 ML/day. During higher flow event at Barmah (around 85, 000 ML/day) the floodplain of the reach is completely inundated. When the cumulative flow of the River Murray at Tocumwal and the Goulburn River at McCoys Bridge is at around 125,000 ML/day, the floodplain downstream of the Kotupna complex is completely inundated.

The available inundation mapping shows most of the flow remains in channel up to around 25,000 ML/d, after which widespread inundation across the floodplain.

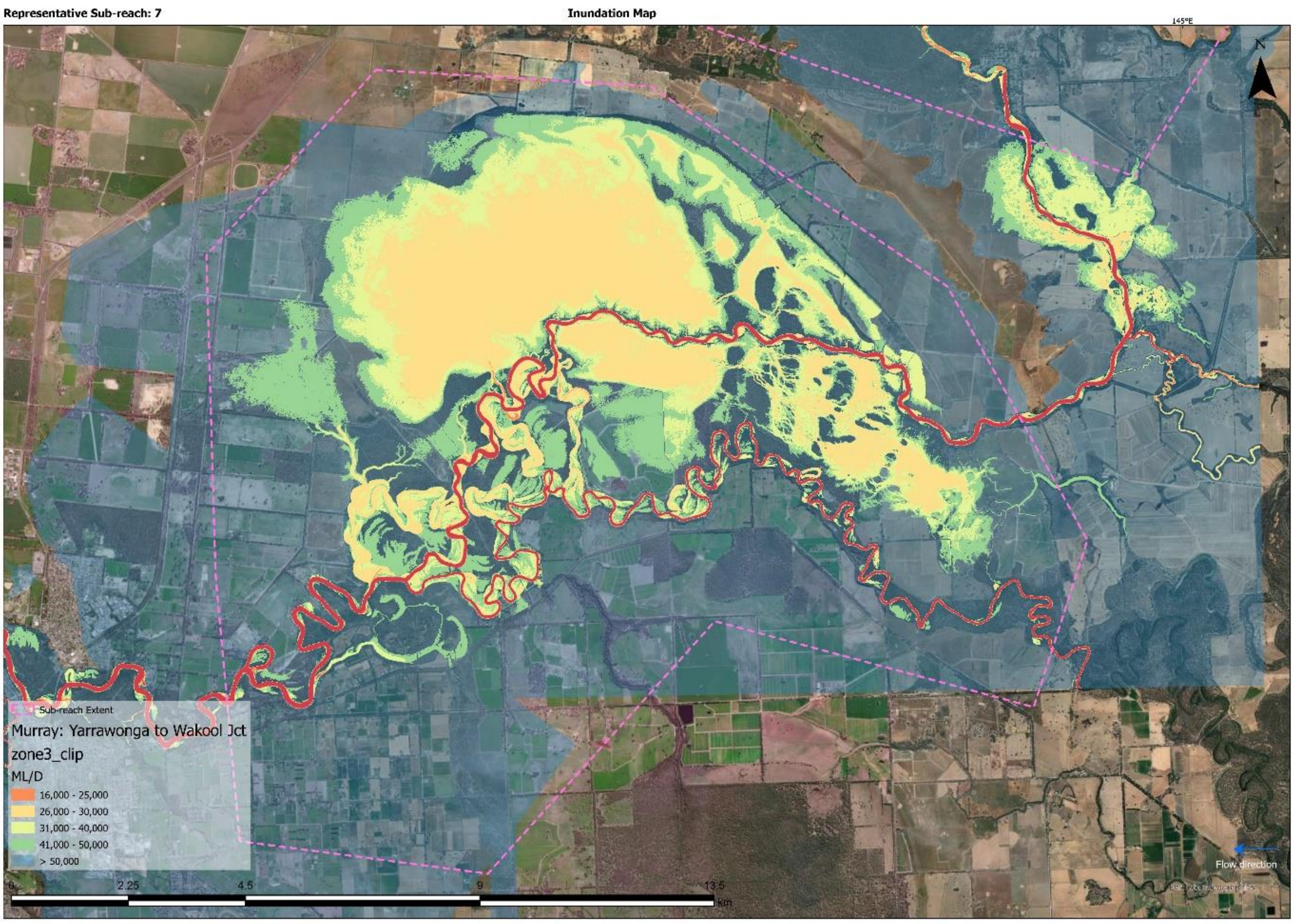

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

g. Form (mainly based on LiDAR)

Baky (2018) used LiDAR based geomorphic mapping to show the area has abundant small depressions across the floodplain. Usually, they are located several meters behind the riverbank levee crest, with some being large enough to be located adjacent to the riverbank margin. Levee channels are also common across the sub-reach. Usually, levee channels with shorter lengths are not directly connected with the river, and they are sloped towards the floodplain. Conversely, the longer levee channels are well connected to the river, and they slope towards the river. There are a small number of meander cutoffs around the River Murray and the Goulburn River junction.

h. Processes

The hydro-geomorphic processes on the floodplain are balanced by the flow distribution between the Goulburn River and the River Murray. At bankfull, the floodplain develops via levee channels depositing flow and sediments onto the floodplain. When the main channel flows from both the Goulburn River and the River Murray start overtopping the banks, erosion may replace deposition as the dominant floodplain development process. This may result in levee channel development processing in an up-channel direction which and potentially results in avulsion development (e.g., near Moira).

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (bar)	Deposition
Channel (benches)	Deposition
Floodplain (levee)	Deposition
Floodplain (sub-bankfull – anabranch/flood runners/rill channels/ connected levee channels)	Most likely deposition at this stage. Avulsion
Floodplain (>bankfull – anabranch/flood runners/rill channels/ connected levee channels)	Deposition is replaced by erosion predominantly at the inlets with the main channel. Avulsion
Floodplain (>bankfull connection)	Deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 7 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows:

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Benches	Deposition	2	3	3	1	1
Bars	Deposition	1	2	3	3	3
Levee	Deposition	0	0	2	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.82**	**0.58**	**0.34**	**0.12**
Likelihood (Y45D40 events per year)		0.99	0.90	0.63	0.35	0.12
Likelihood (Y30D30 events per year)		0.99	0.90	0.62	0.35	0.12

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.7	5.9	4%	5.9	3%
Benches	6.7	7.1	6%	7.0	5%
Bars	5.8	6.1	6%	6.1	5%
Levee	2.5	2.7	5%	2.7	4%
Anabranches / Floodrunners (sub-bankfull)	4.8	5.1	8%	5.1	6%
Floodplain (> bankfull)	1.4	1.4	2%	1.4	2%
Anabranches / Floodrunners (> bankfull)	1.4	1.4	2%	1.4	2%
Wetlands, billabongs, distributary channels	3.1	3.3	6%	3.3	5%
Average	**3.9**	**4.1**	**5%**	**4.1**	**5%**

The channel in this sub-reach is prone to erosion through the process whereby it originally development when the river channel cut through the floor of the Kanyapella paleolake. The crevasse-splays on the floodplain play a major role in floodplain inundation and overall geomorphic floodplain development occurs through both deposition and erosion processes. Avulsion remains a potential factor in floodplain develop and change and there is a potential avulsion course visible near the Moira Forest. Although the paleochannel in the Kotupna complex is an example of a past avulsion event, it remains unclear whether the avulsion was triggered by the Goulburn River or by the River Murray.

Bank erosion is occurring throughout the reach predominantly through notching of the banks under regulated conditions. This is enhanced by boat wake impacts.

Bank erosion and potential avulsion development are significant geomorphic processes occurring under the base case conditions for sub-reaches 7 together with potential deposition on banks, bars and levees under higher flow conditions as indicated by their impact scores. The trajectory for the reach is for these processes to continue under current constraints, with the potential for an increase in the rate that these processes are occurring with an increase in sub-bankfull high freshes and bankfull flows under the proposed flow options.

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Baky, M.A.A., 2018. Floodplain avulsion channels: understanding their distribution and how they reconnect to the parent channel.

Bowler, J.M., 1978. Quaternary climate and tectonics in the evolution of the Riverine Plain, southeastern Australia.

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Rutherfurd, I., 1994. Inherited controls on the form of a large, low energy river: the Murray River, Australia. Variability of Large Alluvial Rivers. ASCE, New York, 177-197.

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Stone, T., 2006b. Late quaternary rivers and lakes of the Cadell Tilt Block region, Murray Basin, southeastern Australia.

Sub-Reach 8 Geomorphic Outline – Perricoota Reach

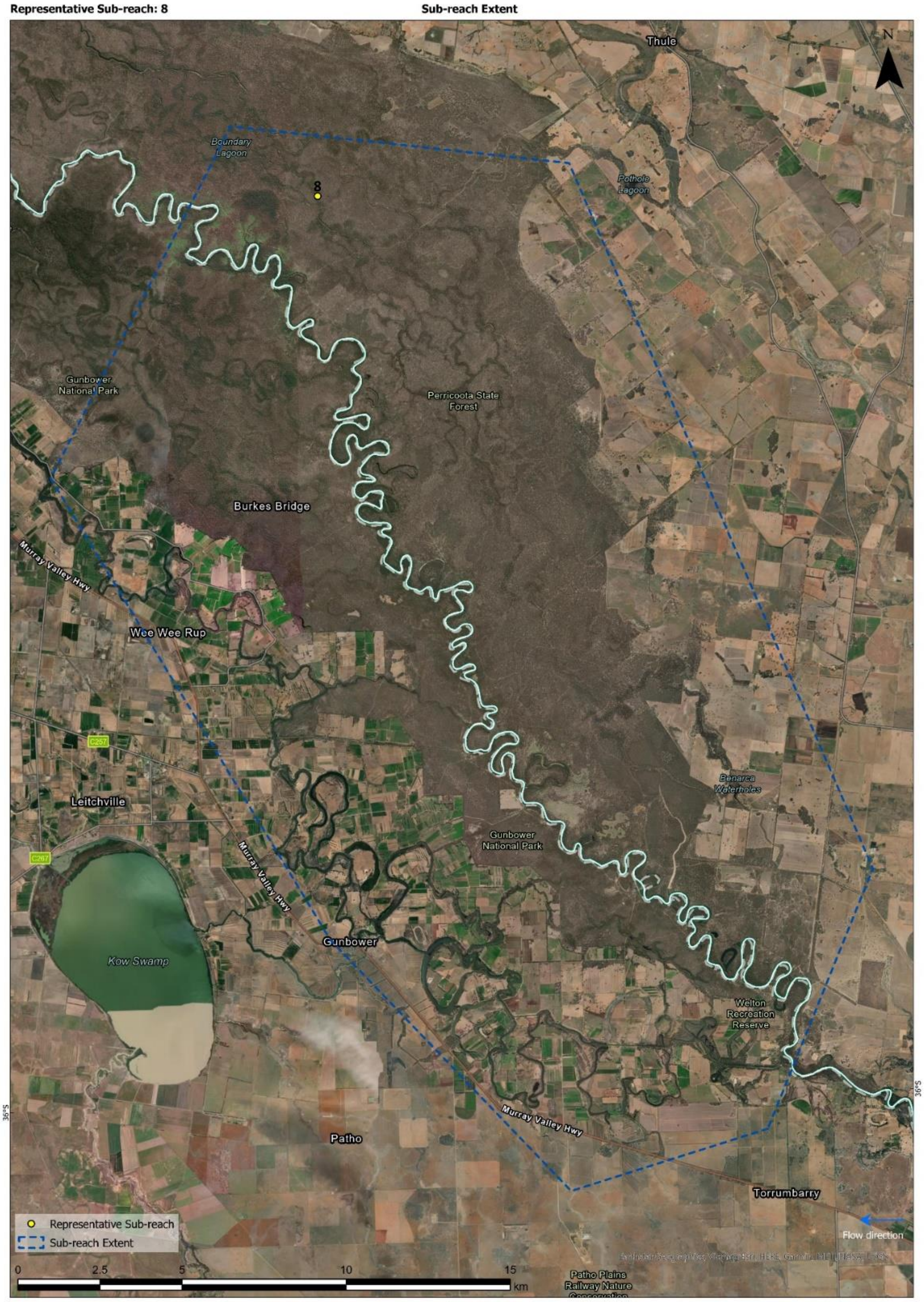

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The sub-reach is on the River Murray with the Torrumbarry Weir near the upstream end, and the reach extends for a valley distance of 32 km. It is downstream of the main tributaries of the Ovens, Goulburn and the Campaspe Rivers and Broken Creek. Flows are regulated upstream by Dartmouth Dam (3,856 GL), Hume Dam (3,005 GL), Yarrawonga Weir (118 GL), Lake Eildon (3,334 GL), Lake Eppalock (305 GL) and Torrumbarry Weir (37 GL) (Hale and SKM, 2011).

The right hand side of the channel and floodplain are part of the Koondrook- Perricoota Forest. Under natural conditions overbank events, the flow would have entered Swan Lagoon into the Burrumbury Creeks. These creeks include several deep, well-defined channels which change downstream into a myriad of smaller, interlinked runners which eventually coalesce into several defined streams at the downstream extent of the reach. The most substantial of these streams is Myloc Creek. On the left bank floodplain is the Gunbower National Park. Like Koondrook-Perricoota, under natural conditions, the forest was inundated once flow events in the Murray River exceeded the commence to flow levels for forest floodrunners such as Yarran Creek and Camerons Creek. The floodplain forest on both the left and right banks of the Murray River through this reach comprise the Gunbower-Koondrook-Perricoota Living Murray Icon site, one of 6 icon sites across the Murray Darling Basin identified for its significant ecological assets.

2. Channel form and processes

a. Anthropogenic changes

To aid navigation of paddle steamers extensive sections of the River Murray were desnagged, it is uncertain when and to what extent this reach was desnagged but it was a used navigation and undoubtedly had wood removed from the channel. Torrumbarry Weir was built between 1919 and 1924. It allowed water to be diverted down the National Channel by gravity. It was damaged in 1992 and a new weir was put into operation in 1997. The weir pool would be expected to settle out some coarse sediment transported as bedload.

b. Historic changes based on the historical imagery

There were few observable changes in channel position between the 1964 back and white aerial photographs and the 2021 Maxar satellite imagery. The extent of steep bare banks on the outside of meander bends appeared similar, the instream wood loads were low and there were no significant bar forms.

c. Forms (mainly based on LiDAR)

The channel is meandering, described as having tortuous meanders in the RiverStyles data. Thoms (2017) reports a sinuosity in this area of 2.12-3.21 and a floodplain width that exceeds 30 km. There are natural levees on the banks.

d. Processes

In the weir pool of Torrumbarry Weir Thoms (2017) found the riverbank sediments to be Silty Clay Loams and Silty Loams. The results of Emerson tests on these sediments were that their aggregate soil stability was low with only 19 % of the sediments tested being stable. This suggests that the bank sediment may slake and disperse. Notching was considered by Thoms (2017) to be the dominate erosion process in the weir pool. Other mass failures observed were block failure, cantilever failure, rotational slipping and bank slumping. The effects of boat wakes on erosion processes are also of concern (Soil Conservation Service, 2018).

Soil Conservation Service have undertaken partial cross-section surveys for sites from Mulwala Weir to Torrumbarry Weir with several sites located within this sub-reach. The results available to date (Soil Conservation Service, monitoring database accessed online) showed 0.4 m of retreat from 2019 to 2022 (0.13 m/year) in the upper bank for the outside bend site closest to Torrumbarry Weir (PX-36), and 2.02m of retreat in the upper bank between 2015 to 2022 (0.29 m/year) for site PX_30 located a couple of outside bends upstream.

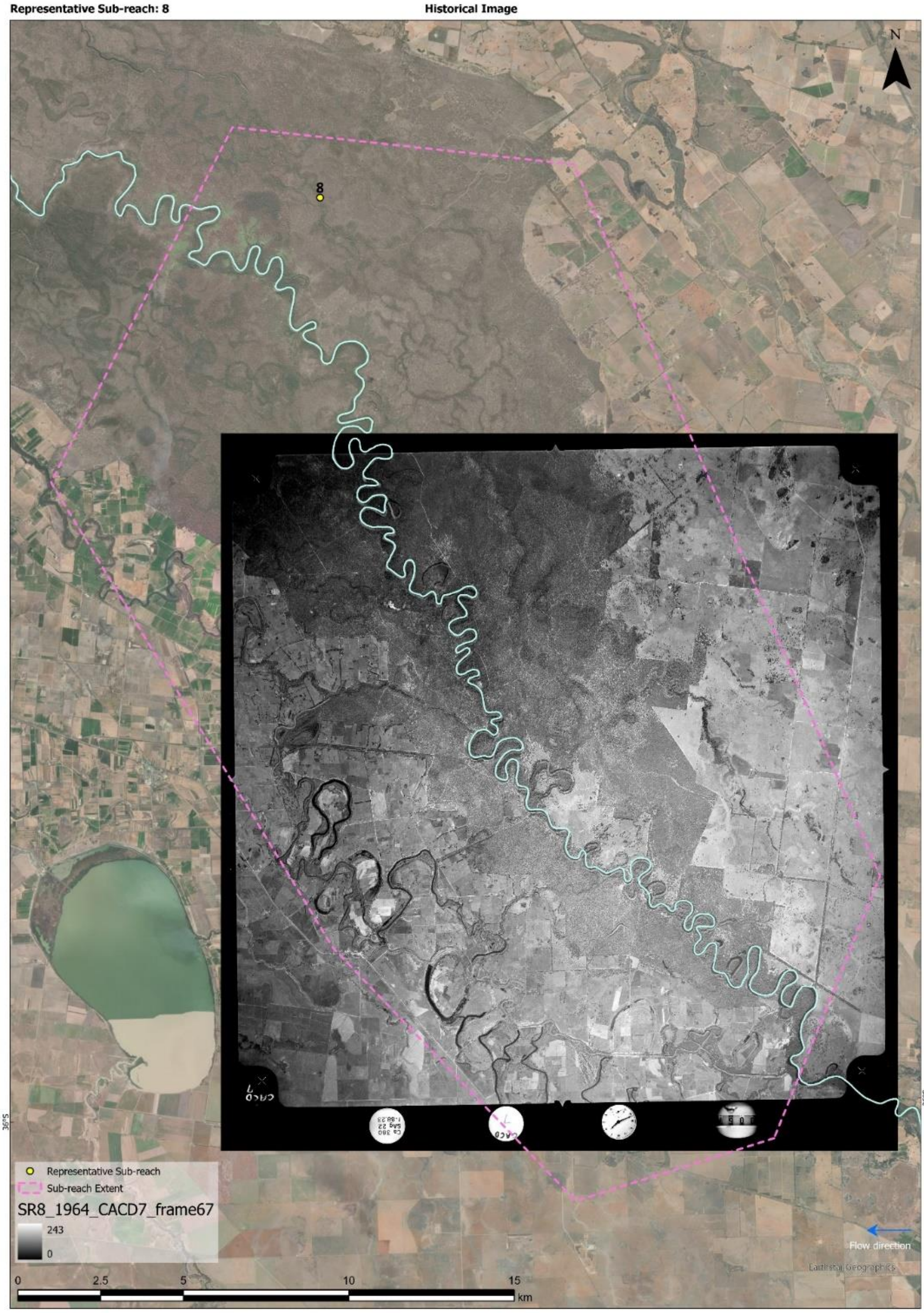

Figure 2 Historic imagery (circa 1964) of the sub-reach extent

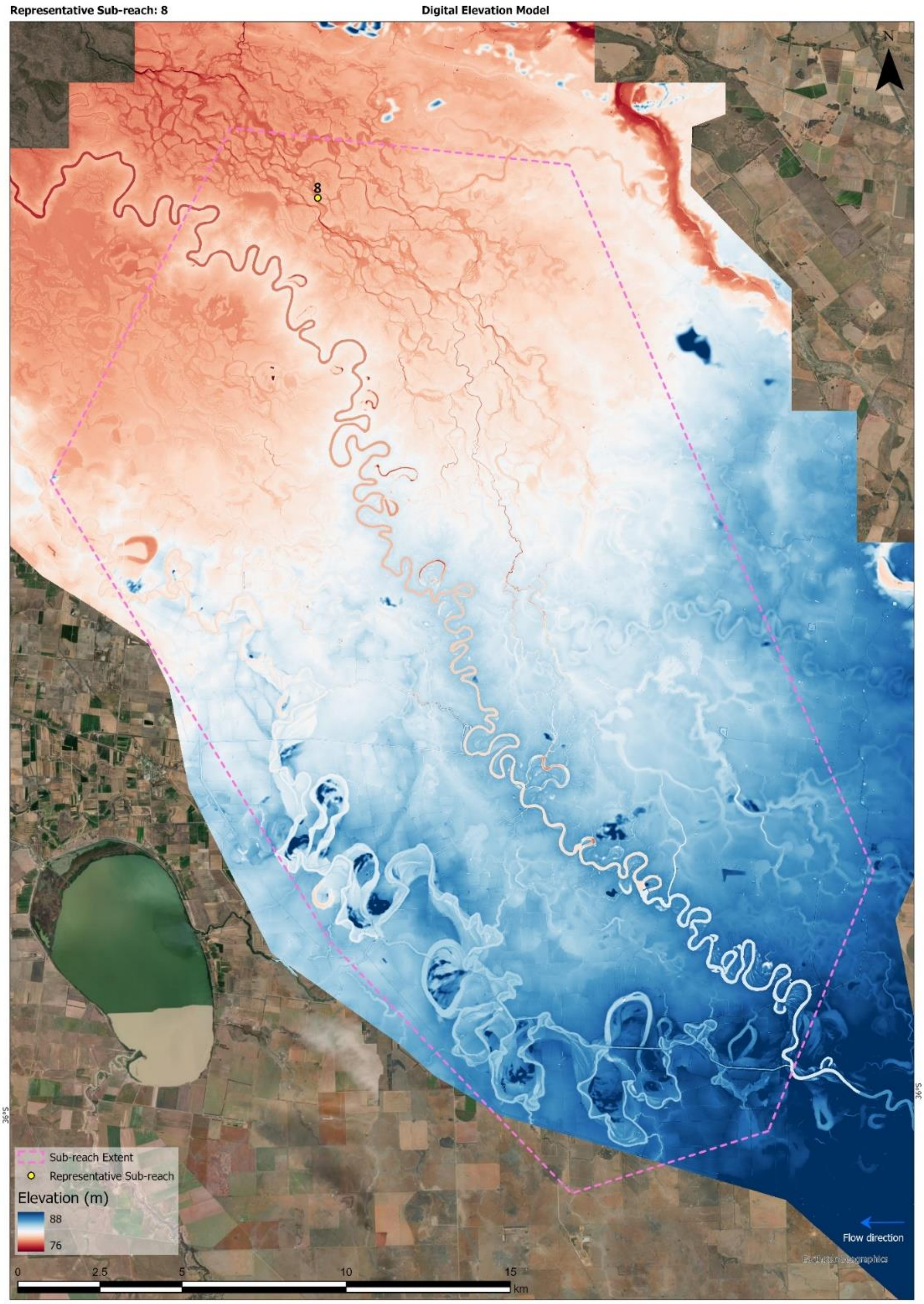

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

3. Floodplain form and process

e. Anthropogenic changes

There are submissions under the Water Act (1912-1966) for levees to be built to prevent the inundation of land by Burumbury Creek in 1952, 1953, 1969, 1972,1973, 1985. As part of The Living Murray Project, a channel has been cut into the forest to deliver environmental flows that are designed to diffuse out from the channel. Regulators have been placed in Swan Lagoon to stop return flow. Other regulators have been constructed to stop flow returning into the Murray and to maintain water on the forest. Downstream of the study reach levees have been constructed.

Within the Gunbower Forest floodplain there have been significant changes to flow and inundation patterns. Within the reach, there are historical flow regulating structures at many floodrunners. This upper section of the Gunbower Forest is also earmarked for future works under the Victorian Murray Floodplain Restoration Project with planned regulating structures at Broken Axle Creek, Spur, Creek, Deep Creek, Old Straight Cut Channel and Camerons Creek. Within the forest immediately downstream of the reach, a significant amount of works have already been undertaken through the Living Murray Program. Regulating structures (Barham Cut Regulator, Shillinglaws Regulator) have been constructed on key floodrunners along the Murray River banks. These regulators can exclude commence to flow events in these floodrunners and also allow for the release of water from the forest into the Murray River. The forest is now inundated via Gunbower Creek with the primary flow delivery point at the constructed Hipwell Road channel which delivers water from the Creek into the Forest. There are also several additional regulators along Gunbower Creek (Black Swamp Regulator, Reedy Lagoon Regulator, Yarran Regulator, Little Gunbower Regulator) that allow key wetland areas (Reedy Lagoon, Black Swamp etc.) to be watered directly from Gunbower Creek.

f. Hydrological connections

There are several secondary inflow points downstream of Swan Lagoon, although of much smaller scale. The most significant of these are Horseshoe Lagoon and Dead River, as well as the Black Gate, Penny Royal, Thule and Crooked Creeks. Outflow primarily occurs at Thule Creek, Barbers Creek, Calf Creek and Cow Creek into the Wakool River system. During large flood events water also drains out of Axe Creek and Pothole Creek.

Downstream of Swan Lagoon are a number of other oxbow lagoons, several of which have associated natural effluents that form secondary inflow points at very high flows in the Murray (Harrington and Hale, 2011). Horseshoe Lagoon and Dead River Lagoon. As river levels rise higher, an increasing number of these smaller channels begin to flow. Substantial broad area flooding occurs when the flows exceed the channel capacity of the Murray River (greater than 30 000 megalitres per day). It is estimated that at flows of 35 000 megalitres per day approximately 80 percent of the river red gum forest is inundated.

The rate of flow on the floodplain surface during reported by Dind (2018) varied from >5 km/day upstream to 0.18 km/day further downstream. Flow thresholds at locations in the Koondrook Perricoota Forest are summarised in Dind (2018).

Inundation mapping shows the main channel capacity is around 15,000-25,000 ML/d with increasing floodplain inundation from 15,000 ML/d to 50,000 ML/d. However, the inundation is constrained to the forested floodplain sections due to regulators and levees.

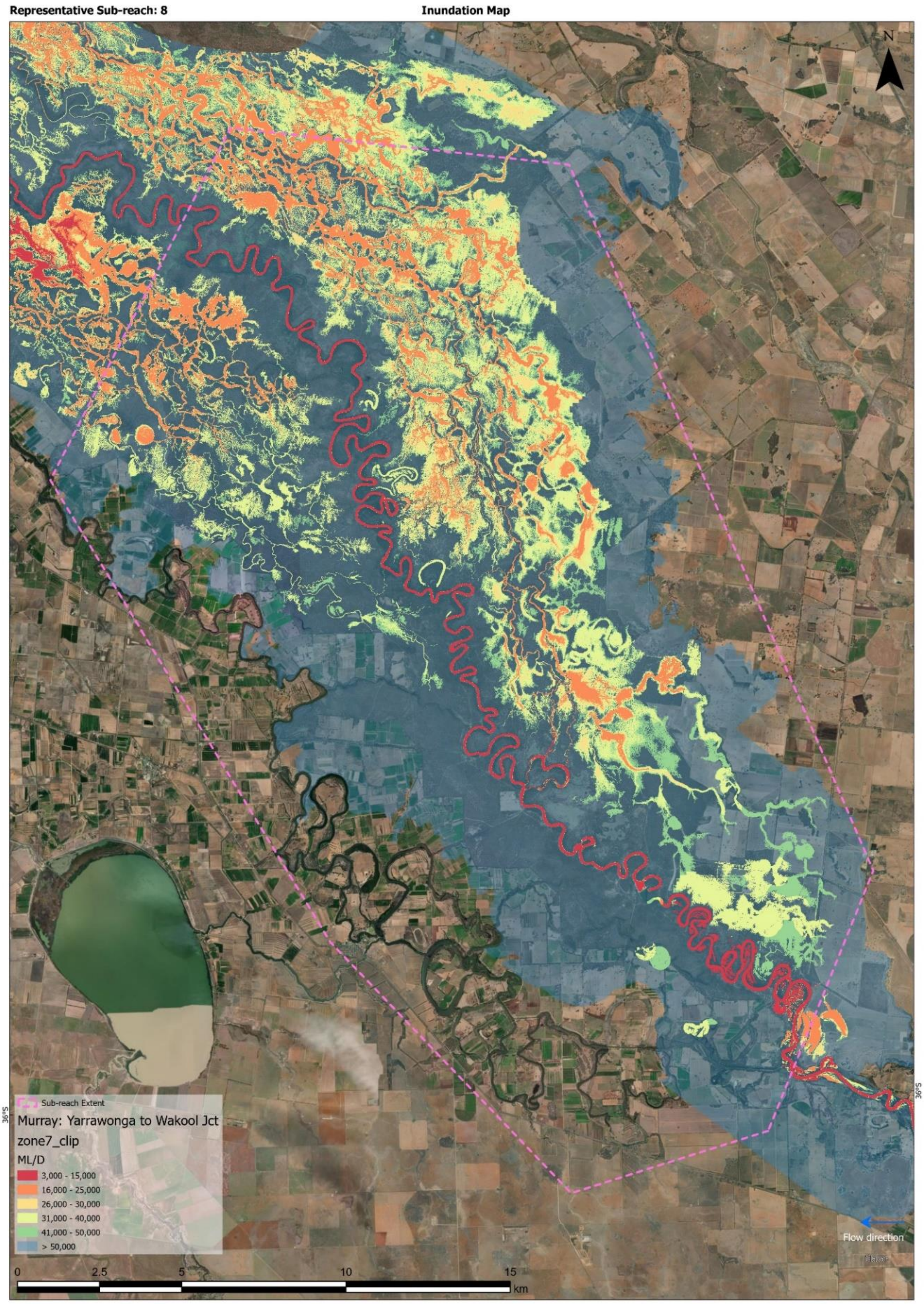

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

g. Form (mainly based on LiDAR)

Thoms (2017) describes these floodplains as having geomorphic features that include contemporary and relict meanders, distributary, and anabranch channels along with numerous billabongs, deflation basins and shallow lakes. The LiDAR data shows the network of small channels with some pinnate drainage networks.

h. Processes

The processes of erosion and deposition on the floodplain are a balance between the length and rate of flow, the sediment volumes delivered in the flows and the vegetation. Infrequent inundation and low sediment yields mean that rates of change are low. However, care will need to be taken not to supply too much sediment, and associated nutrients that create high vegetation growth, and then then supply more water and sediment. This may cause sediment to be deposited more quickly and create higher boundary velocities making channels enlarge.

4. Base case

The base case geomorphic features and processes are summarised Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition
Floodplain (Wetlands, billabongs, distributaries)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 8 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows:

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Output flow information Torrumbarry have been used for assessing the flow options scenarios.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.82**	**0.58**	**0.34**	**0.12**
Likelihood (Y45D40 events per year)		0.99	0.90	0.63	0.35	0.12
Likelihood (Y30D30 events per year)		0.99	0.90	0.62	0.35	0.12

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.7	5.9	4%	5.9	3%
Anabranches / Floodrunners (sub-bankfull	4.8	5.1	8%	5.1	6%
Floodplain (> bankfull)	1.4	1.4	2%	1.4	2%
Anabranches / Floodrunners (> bankfull)	1.4	1.4	2%	1.4	2%
Wetlands, billabongs, distributary channel	3.1	3.3	6%	3.3	5%
Average	**3.3**	**3.4**	**5%**	**3.4**	**4%**

Under base case conditions, in-channel processes upstream of Torrumbarry Weir are dominated by bank erosion associated with lateral bend migration which is enhanced by the regulated river level associated with the weir pool operation and boat wakes.

Downstream of the weir, floodplain connections and flooding are largely controlled by the offtake and regulators and processes such as avulsion development associated with sub-bankfull flows are largely restricted by the offtakes and regulators. Bank erosion can occur because of the operation of offtakes and regulators, particularly rapid changes in water level.

The future trajectory of this sub-reach is for continued bank erosion associated with constant prolonged flow conditions. Under the flow options scenarios there is limited change in the flow regime for this sub-reach compared to base case (current constraints) and a measurable increase in the rate of change associated with existing geomorphic processes is unlikely to occur.

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes

7. References

Dind, J. (2018). Koondrook-Perricoota Forest Monitoring – Flood Monitoring 2018. Unpublished report by Forestry Corporation of New South Wales.

Hale, J and SKM (2011). *Environmental Water Delivery: Koondrook-Perricoota Forest.* Prepared for Commonwealth Environmental Water, Department of Sustainability, Environment, Water, Population and Communities.

Harrington, B. and Hale, J., 2011, Ecological Character Description for the NSW Central Murray Forests Ramsar site. Report to the Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Thoms, M., 2017. Bank instability along a weir pool of the River Murray. *Transactions of the Royal Society of South Australia*, *141*(2), pp.151-168.

Sub-Reach 9 Geomorphic Outline – Perricoota Reach (Koondrook Perricoota)

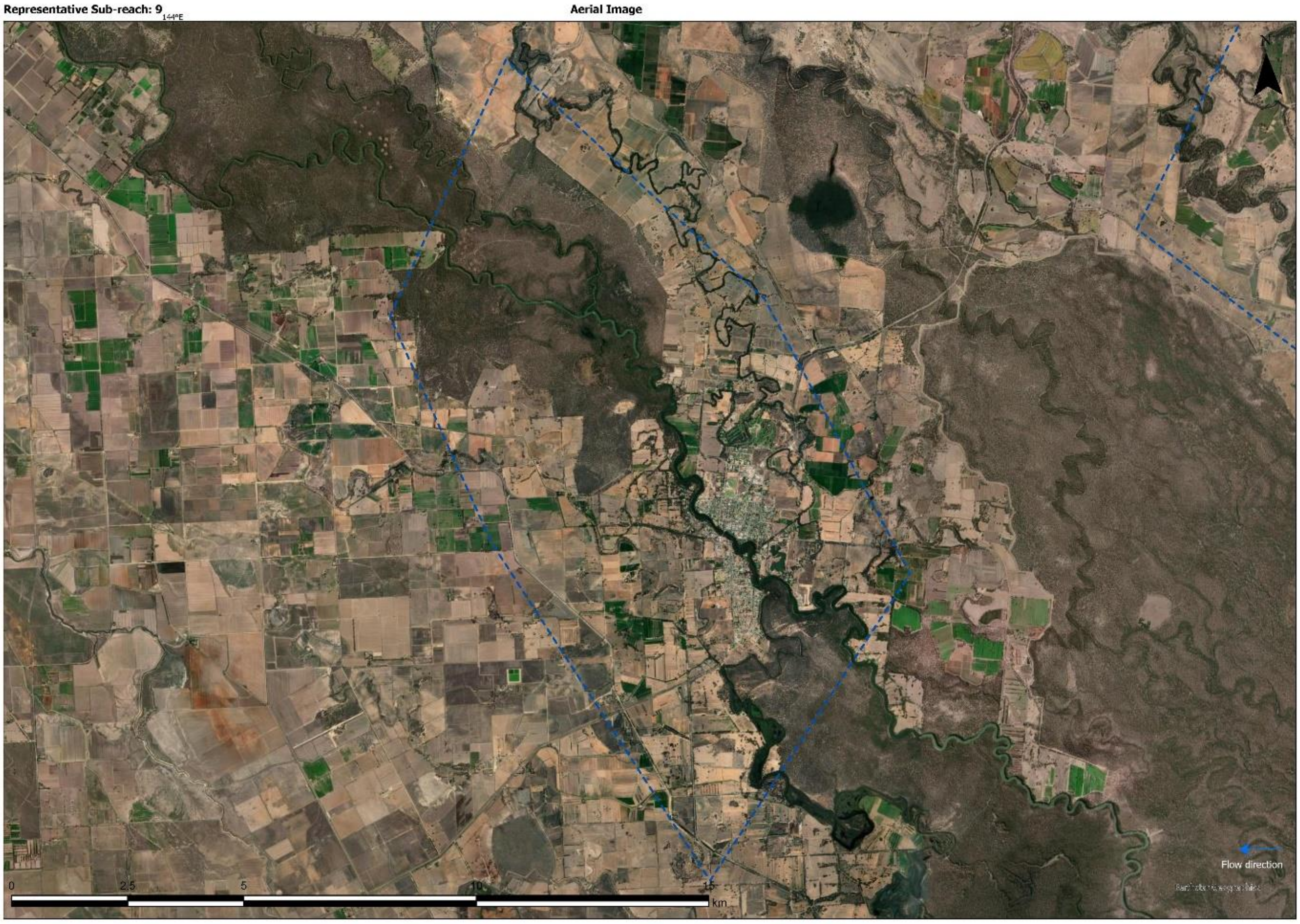

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

Sub-reach 9 is located on the Murray River and extends from just upstream of Barham to the upstream extent of Campbells Island State Forest. The reach is influenced by flows from the main Victorian tributaries and is highly regulated with flows stored upstream of the reach in the Torrumbarry Weir Pool and distributed to the region for irrigation. Flows are also regulated on the floodplains along the reach on both the NSW and Victorian floodplains of the Murray River. On the Victorian floodplain, the reach extends from the Lower Gunbower Forest which is a part of the Living Murray Program to Guttrum State Forest. On the NSW floodplain, the reach extends from an area just south of the Koondrook-Perricoota Forest to the upper extent of the Campbells Island State Forest. The Gunbower and Koondrook-Perricoota Forests comprise the Living Murray Icon Site and the NSW floodplain forest form the NSW Central Murray Ramsar Site.

2. Channel form and processes

a. Anthropogenic changes

The key changes that have impacted on the reach are those associated with flow regulation. Upstream of the reach there are a number of storages and flow diversion points which have results in a decrease flow volume. Desnagging of the channel within this reach, as with other reaches along the Murray River have also had and influence on the changes in channel morphology within the reach.

b. Historic changes based on the historical imagery

There were few observable changes in channel position between historical imagery and current aerial imagery. Downstream of Barham there appears to minor shifts in channel position which appear to be most likely associated with meander migration. Other changes in channel morphology within the reach have previously been identified by Gippel and Blackham (2002). In-channel morphology within the reach was described as variable although an accelerated loss of benches due to constant regulated flows was noted (Gippel & Blackham 2002). In addition, riverbank erosion and notching have also been highlighted as characteristic downstream of Torrumbarry Weir.

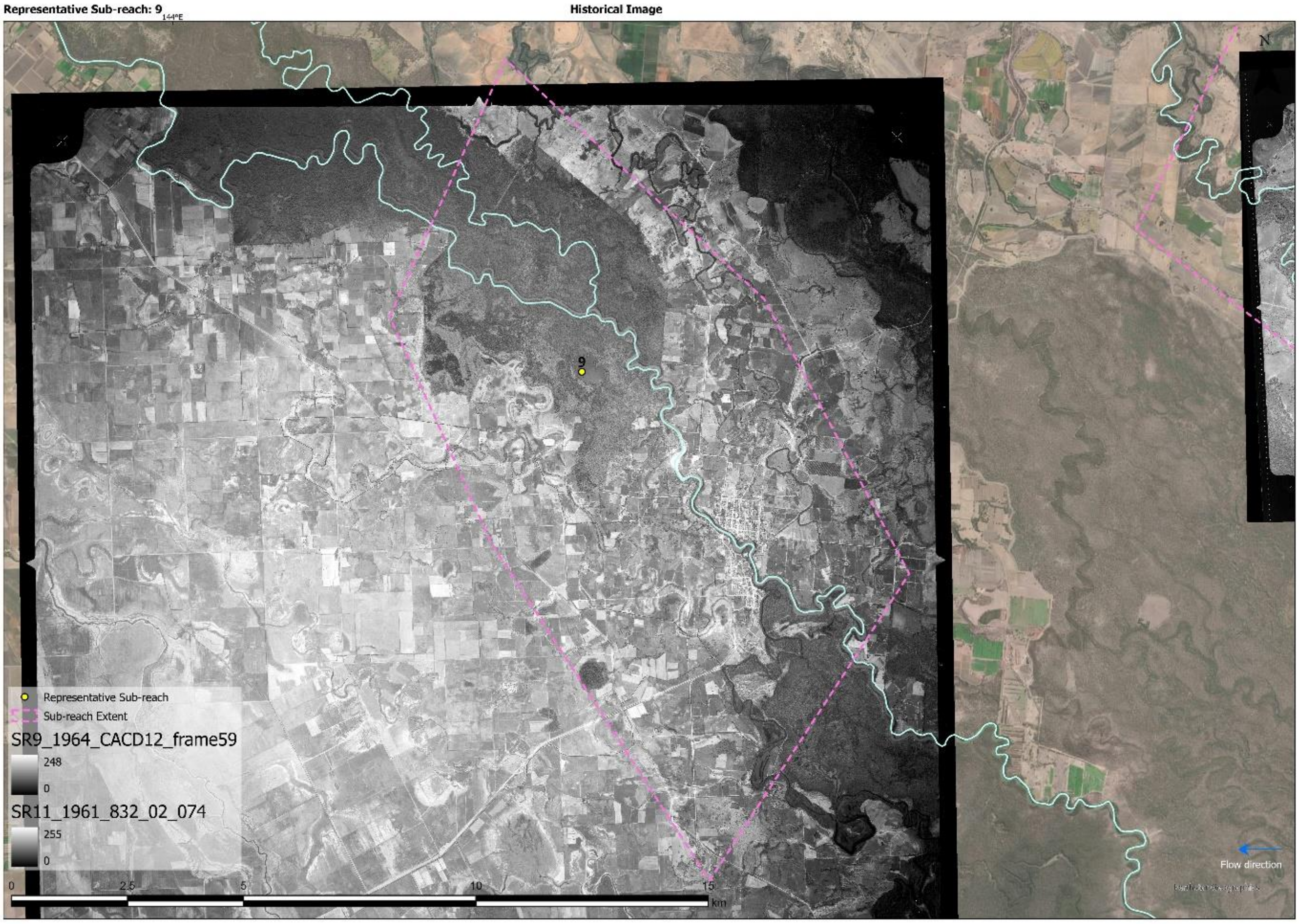

Figure 2 Historic imagery (circa 1964) of the sub-reach extent

c. Forms (mainly based on LiDAR)

The channel in this reach is low sinuosity, meandering as classified by the RiverStyles Framework. Within this reach the channel is well defined and has an extensive network of both natural and constructed levees to contain mid-sized river flows.

a. Processes

Bank erosion related to river regulation (notching) have been identified in this sub-reach potentially enhancing natural lateral migration processes. Erosion of in-channel benches due to regulated flows is also occurring.

3. Floodplain form and process

b. Anthropogenic changes

The upstream extent of the reach includes Eagle Creek and the lower part of the Koondrook-Perricoota Forest on the NSW floodplain and the Lower Gunbower Creek and Gunbower Forest on the Victorian floodplain. A range of flow regulating structures and channels have been built in both Koondrook-Perricoota and Gunbower Forests through the Living Murray Program to assist with the delivery and inundation of these forests to meet their ecological requirements. On the NSW floodplain there are number anabranch channels that provide connection between the Murray and the Edward-Wakool system. Eagle Creek cutting takes water from the

Murray into Eagle Creek which joins Merran Creek. Merran Creek has flow connections to the south, where flow from the Little Murray River at Campbells Island via Merran Cutting can be diverted into Merran Creek. To the north there are flow connections to the Wakool system at Barbers Creek via a series of small anabranch channels, via Merran Creek which joins the Wakool River to the northwest of the reach and through a number of smaller channels the connect Merran Creek with the Wakool such as Mulligans Creek and Erigin Creek. On the Victorian floodplain, Gunbower Creek, a natural anabranch of the Murray River which has been used to deliver water for irrigation rejoins the Murray River. At the downstream extent of the reach, the floodplain includes Guttrum State Forest, which is currently a key component of the Victorian Murray Floodplain Restoration Project which is seeking to improve the achievement of watering requirements for different ecological assets. At Guttrum Forest the intention will be to construct a number of permanent pump stations to facilitate this watering. In the past, interim watering has occurred at key wetlands within the forest such as Reed Bed Swamp using temporary pumping.

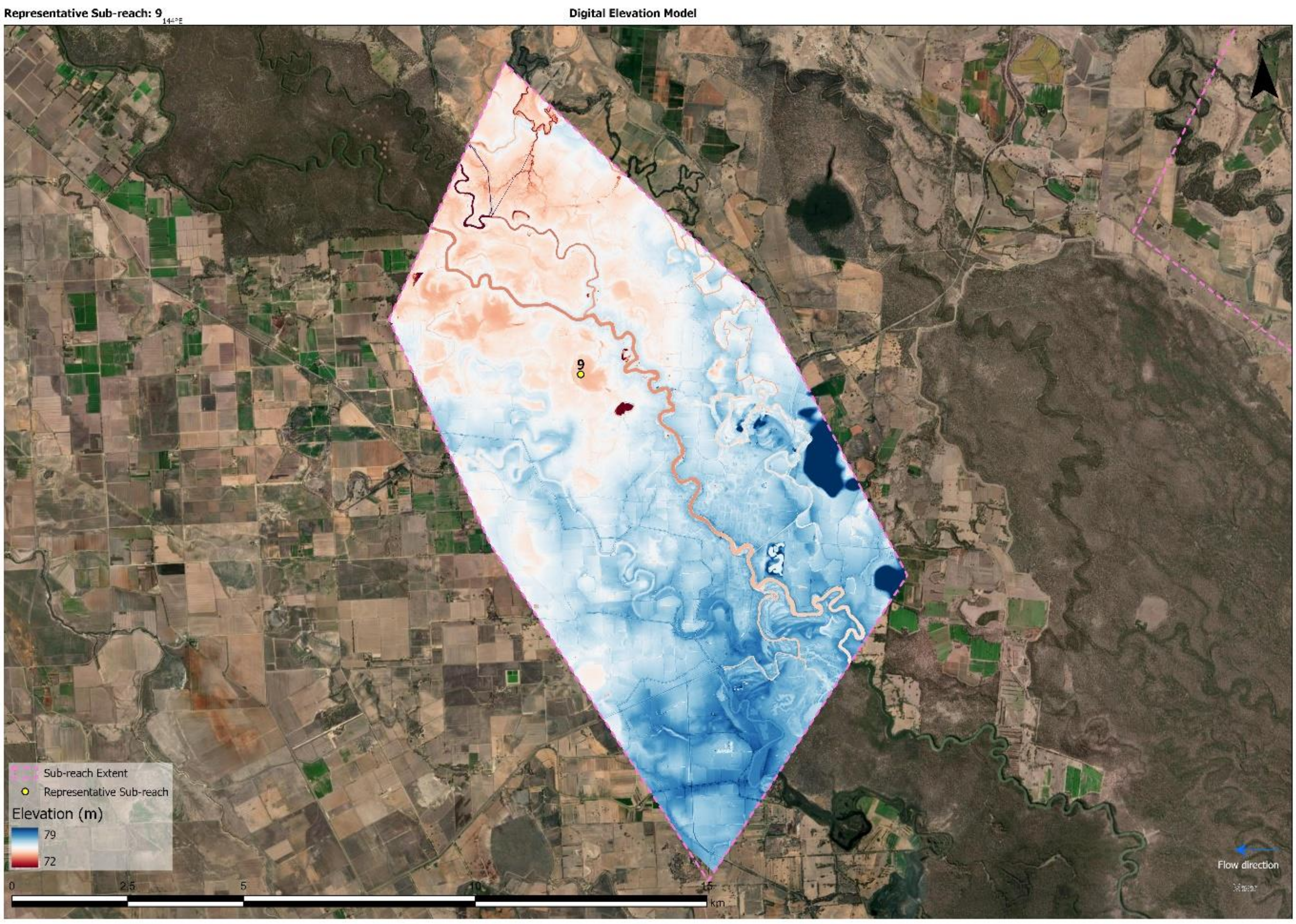

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

c. Hydrological connections

At the southern end of the sub-reach, associated with the Gunbower and Koondrook-Perricoota forests there is little floodplain on the NSW side of the river with inundation below 40,000 ML/d constrained to the forested sections between the River Murray and Gunbower Creek.

Through Barham, flows are confined to the channel over the flow options range.

Downstream of Barham, channel capacity is around 15,000 ML/d with increasing engagement of cutoffs, effluent channels and wetlands across the floodplain at 25,000 in the northern section of the sub-reach. Between 25,000 ML/d to 50,000 ML/d the floodplain extent changes only marginally.

Constructed levees and banks effectively constraint the floodplain outside the forested areas and only flows above 50,000 ML/d would breakout towards the Wakool system to the north.

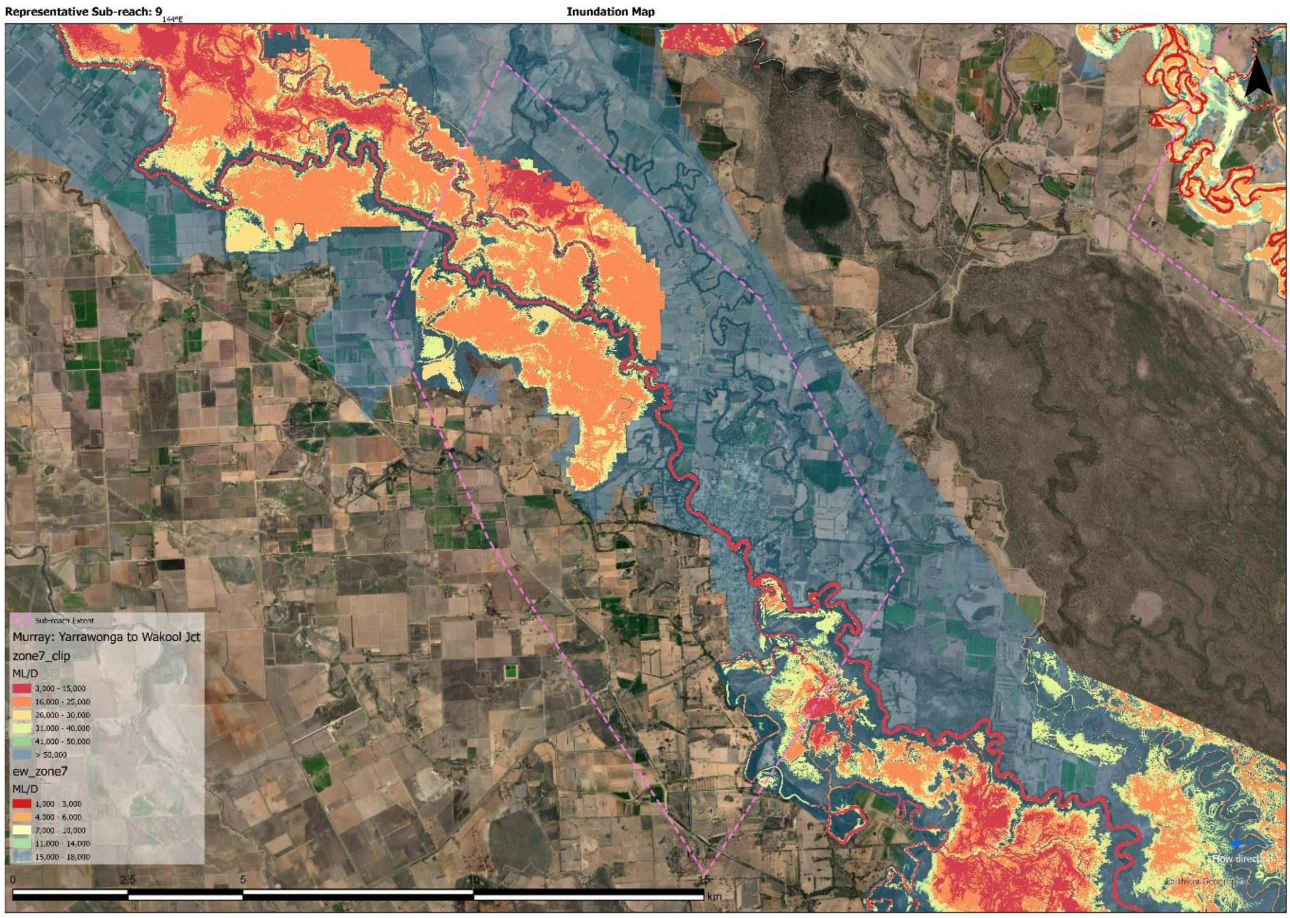

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

d. Form (mainly based on LiDAR)

At the upstream extent of the reach, Gunbower Creek, an anabranch of the Murray River, now largely used to deliver water for consumptive use, re-enters the Murray at Koondrook. At the downstream extent of the reach, the Little Murray River, another anabranch diverts from the main channel. This reach is characterised by channel changes in the form of the development of anabranch channels which can be seen in various stages of development from LiDAR imagery. There is also evidence of meander migration at the upstream extent of the reach near the confluence of the Murray River and Gunbower Creek where there LiDAR shows scroll bars typically associated with this process. A typical floodplain feature along this reach is the presence of billabongs that have been cut off from the main channel at some point in the past. These billabongs scattered across the floodplain now function as floodplain wetlands which play an important role in the biodiversity assets of the region.

e. Processes

The presence of many channels, floodrunners, scroll bars and billabongs indicates that key processes operating within the reach include avulsion and anabranch development, meander migration and meander cut off. These large, reach scale processes appear to be the dominant processes within the reach.

4. Base case

The base case geomorphic features and processes are summarised Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (benches)	Bench edge erosion
Channel (levees)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 9 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows:

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Output flow information Torrumbarry have been used for assessing the flow options scenarios.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Benches	Bench edge erosion	2	2	2	1	1
Cutoffs	Meander migration	1	2	3	3	3
Levees	Desposition	0	0	2	3	3
Cutoffs	Erosion	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.82**	**0.58**	**0.34**	**0.12**
Likelihood (Y45D40 events per year)		0.99	0.90	0.63	0.35	0.12
Likelihood (Y30D30 events per year)		0.99	0.90	0.62	0.35	0.12

The River Murray in this sub-reach is undergoing lateral migration processes which results in erosion of the riverbank at the outside bend of the channel. This natural erosion process is enhanced by river regulation, where notching of the bank occurs, result in mass failure of the bank. Other processes such as avulsions and anabranch development naturally occur within the floodplain. These processes are the base case conditions and are reflected in the impact score for current constraints. The future trajectory of this sub-reach is for continued lateral migration and bank erosion. Under the flow options scenarios there is limited change in the flow regime for this sub-reach compared to base case and a measurable increase in the rate of change associated with existing geomorphic processes is unlikely to occur.

Table 4. Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.7	5.9	4%	5.9	3%
Benches	5.3	5.5	5%	5.5	4%
Cutoffs	5.8	6.1	6%	6.1	5%
Levees	2.5	2.7	5%	2.7	4%
Cutoffs	5.8	6.1	6%	6.1	5%
Anabranches / Floodrunners (sub-bankfull)	4.8	5.1	8%	5.1	6%
Floodplain (> bankfull)	1.4	1.4	2%	1.4	2%
Anabranches / Floodrunners (> bankfull)	1.4	1.4	2%	1.4	2%
Wetlands, billabongs, distributary channels	3.1	3.3	6%	3.3	5%
Average	**4.0**	**4.2**	**5%**	**4.1**	**5%**

6. Limitations and Constraints

There is limited information on bank condition through this reach. Much of the floodplain flows are constrained through regulators or levees and the inundation extents will depend on the operation of the river flows and these control structures.

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Gippel, C.J and Blackham, D. 2002. *Review of environmental impacts of flow regulation and other water resource developments in the River Murray and Lower Darling River system.* Final report by Fluvial Systems Pty. Ltd, Stockton, to Murray-Darling Basin Commission, Canberra, ACT.

Harrington, B. and Hale, J. 2011. *Ecological Character Description for the NSW Central Murray Forests Ramsar Site.* Report to the Department of Sustainability, Environment, Water, Population and Communities, Canberra.

MDBA. 2012. *Gunbower Forest Environmental Water Management Plan*. Murray Darling Basin Authority, Canberra.

MDBA. 2015. *Yarrwonga Weir to Wakool Junction reach report: constraints management strategy.* Murray Darling Basin Authority, Canberra.

NCCMA. 2015. *Gunbower Creek System Environmental Water Management Plan.* North Central Catchment Management Authority, Huntly.

VMFRP. N.D. *Gunbower National Park Fact Sheet.* Victorian Murray Floodplain Restoration Project.

VMFRP. N.D. *Guttrum and Benwell Forests Fact Sheet.* Victorian Murray Floodplain Restoration Project.

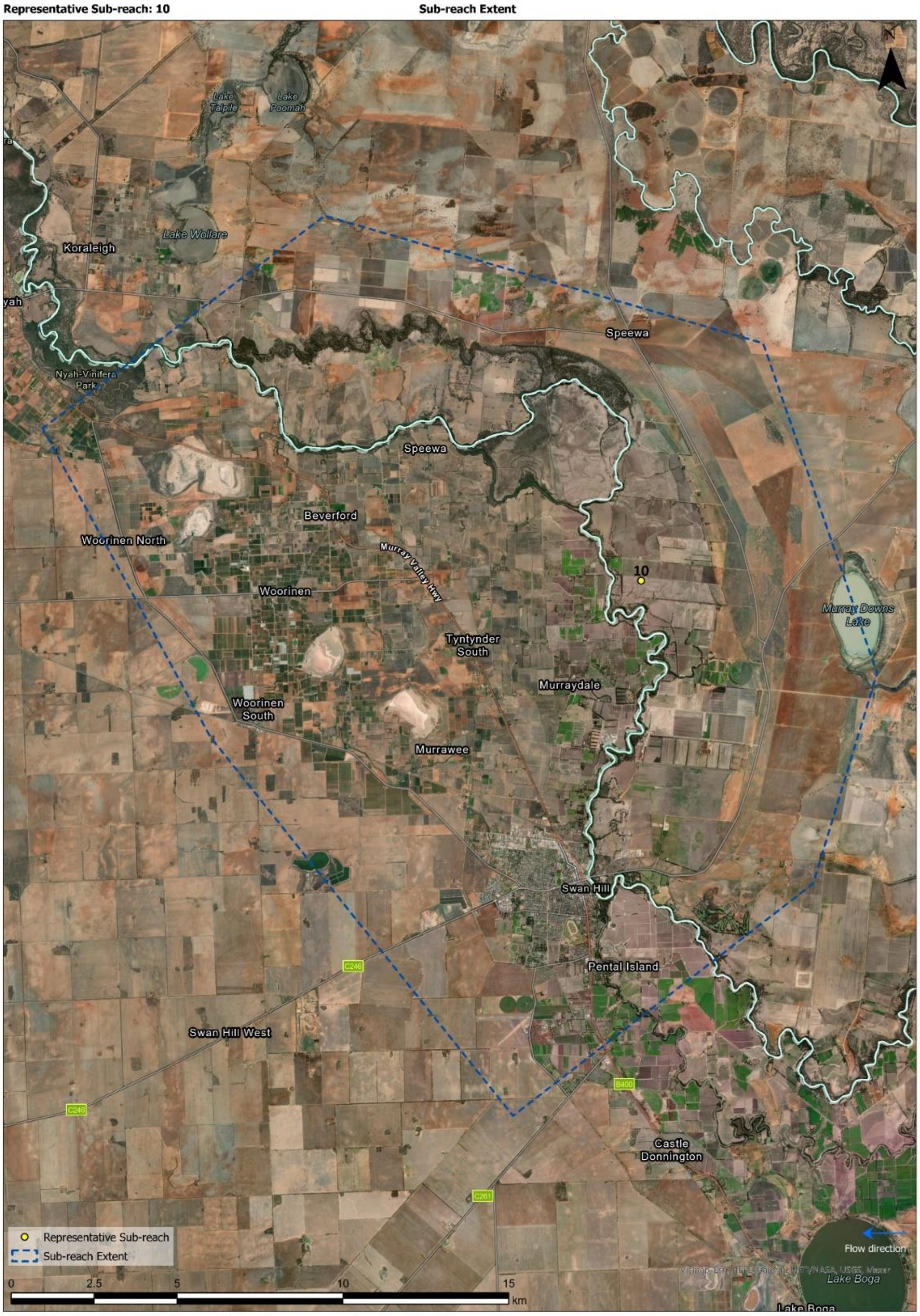

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

This sub-reach of the Murray River is located immediately downstream of Swan Hill in the reach between Torrumbarry Weir and Wakool Junction. It is located towards the boundary of the Lower Alluvial Fan zone and the Bungunnia Zone.

The topography of the defined reach extent is dominated by the Tyntynder palaeolake: an oval-shaped low-relief area bounded to the south-west by a ridge of "red country" and to the east by several lunettes. A string of small remnant modern lakes occupies part of the country at the base of the ridge. The palaeolake is formed at the toe of the lower alluvial fan zone as it approaches the footprint of Lake Bungunnia.

2. Channel form and processes

a. Anthropogenic changes

There are irrigation offtakes and channels and associated levees on the floodplain. There are several locations where offtakes extract irrigation water directly from the main river channel to floodplain irrigation channels.

b. Historic changes based on the historical imagery

No large-scale planform changes are visible from the 1964 aerial photography. In channel bars and benches show variability over time in more recent imagery (Google imagery 2005 to 2021).

c. Landforms

At the upstream end of the sub-reach, the Little Murray River anabranch of the Murray River re-joins the main river at Swan Hill, this creates an area known as Pental Island. The Loddon River has a direct outfall into the Little Murray, while the Avoca River has flows which eventually enter Lake Boga and then via the outfall into the Little Murray. Extensive floodplain levee systems exist along the system this provides protection to support irrigation, agriculture, business, tourism and lifestyle development (SES, 2014).

The flow path is functionally unconfined, and the Murray River becomes anabranching in the north, with branches enclosing Beveridge Island and another area between the Murray River and Speewa Creek. At the downstream end of the defined reach extent, the Murray River enters a more confined valley that cuts through slightly elevated country to the north. In the defined reach extent, the Murray is gently to tightly sinuous but not actively meandering.

The Murray River channel and River Murray anabranch are irregularly sinuous, with the sinuosity varying from open to tight. The Speewa Creek channel is smaller and more tightly sinuous. Channel sinuosity is not associated with any scroll plain landforms, nor are there point bars visible in the channel. The lidar data shows several ancestral channels of varying scales and degrees of preservation, only some of which are also visible on the satellite image.

Sandy point bars and benches are visible on several sections of the sub-reach north of Swan Hill and show periods of both erosion and accretion over the last 18 years (Google imagery 2003 to 2021).

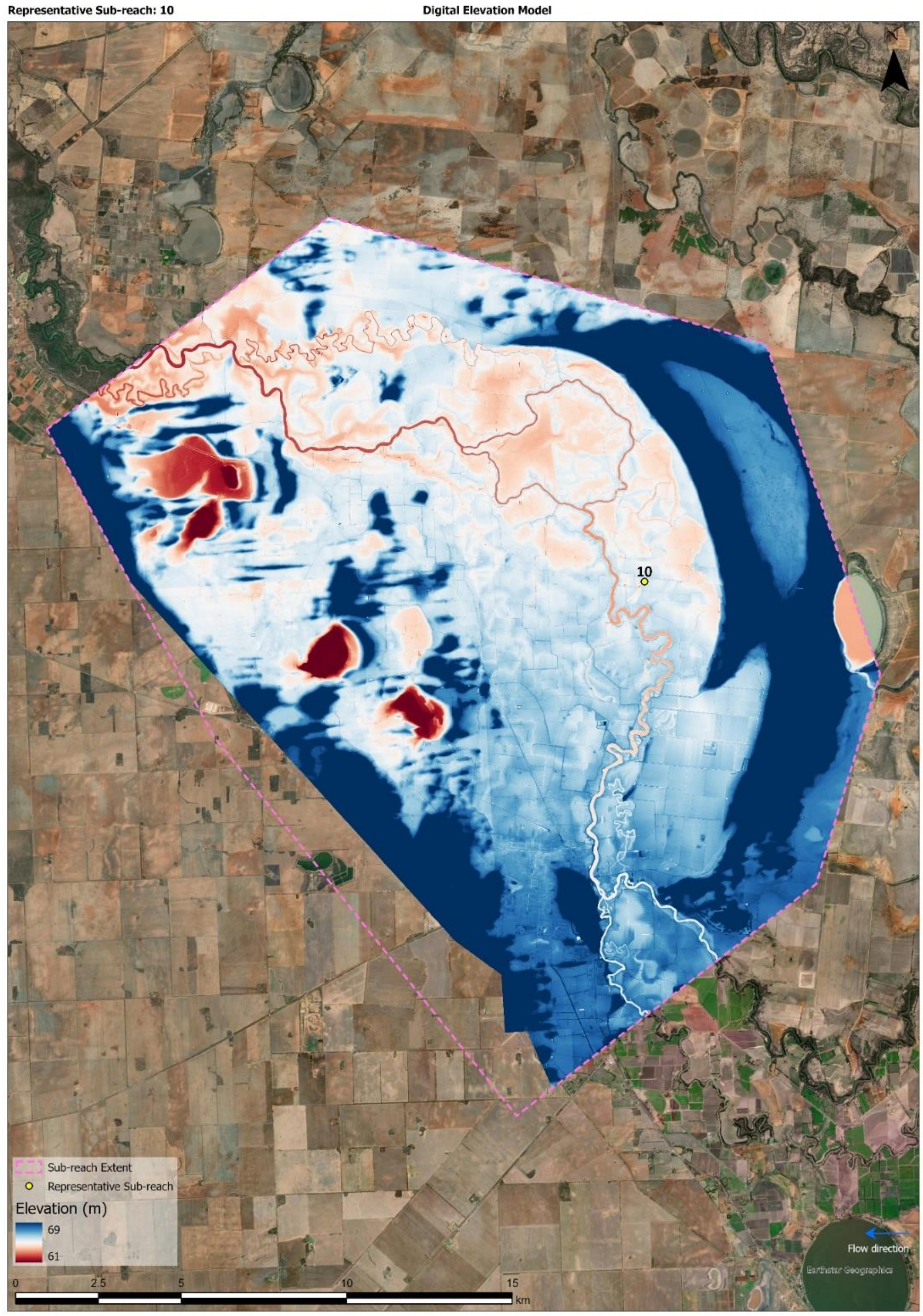

Figure 2 Lidar imagery of the sub-reach showing the different geomorphic features present

d. Processes

The channel planform appears to be static: there is no evidence of incremental channel migration, either in the present day or in the immediate past. The infilled ancestral channels indicate floodplain sediment accumulation, probably by vertical accretion, however it is doubtful that there would have been enough sediment accumulation to completely hide scroll plains. In combination with the flat palaeolake topography and the geometry of the ancestral and present-day channels, it is likely that channel mobility here is by flood-driven channel relocation under backwater conditions.

The absence of natural levees along the channel margins may indicate either little sediment load during flood conditions, or low-energy flood conditions such that sediment travels low in the water column and is not deposited on banktops during overtopping.

3. Floodplain form and process

a. Anthropogenic changes

The palaeolake surface is heavily modified by agricultural development. Flood levees across the sub-reach have significantly modified floodplain inundation patterns.

b. Hydrological connections

In addition to the main River Murray flows this reach can receive flows from the Lodden River via the Little Murray River. Speewa Creek normally only receives water from the River Murray under high flows but environmental water can be pumped into the creek (e.g., OEH, 2015)

Inundation mapping indicate low-elevation areas flanking the main Murray and Speewa channels will experience inundation at >16,000 ML/d to >31,000 ML/d. The flood extent is constrained, likely due to the presence of levee banks, whereas the flood extents for higher flows are limited by the lunette feature at the boundary of the paleolake.

Land use patterns and vegetation extent indicate that most of the palaeolake floor is not regularly inundated.

c. Landform

The wider area of the defined reach extent is mostly modified palaeolake surface, only inundated at >50,000 ML/D. Near the channels, the modern floodplain is of slightly lower elevation than the palaeolake surface, heavily vegetated, and showing traces of infilled ancestral channels. No scroll plain traces are visible.

d. Processes

The infilled ancestral channels indicate floodplain sediment accumulation, probably by vertical accretion during flooding. Modern floodplain is likely to experience low-energy inundation >16,000 ML/D and >31,000 ML/D, adjacent to the channels and the vicinity of Beveridge Island.

Representative Sub-reach: 10 **Inundation Map**

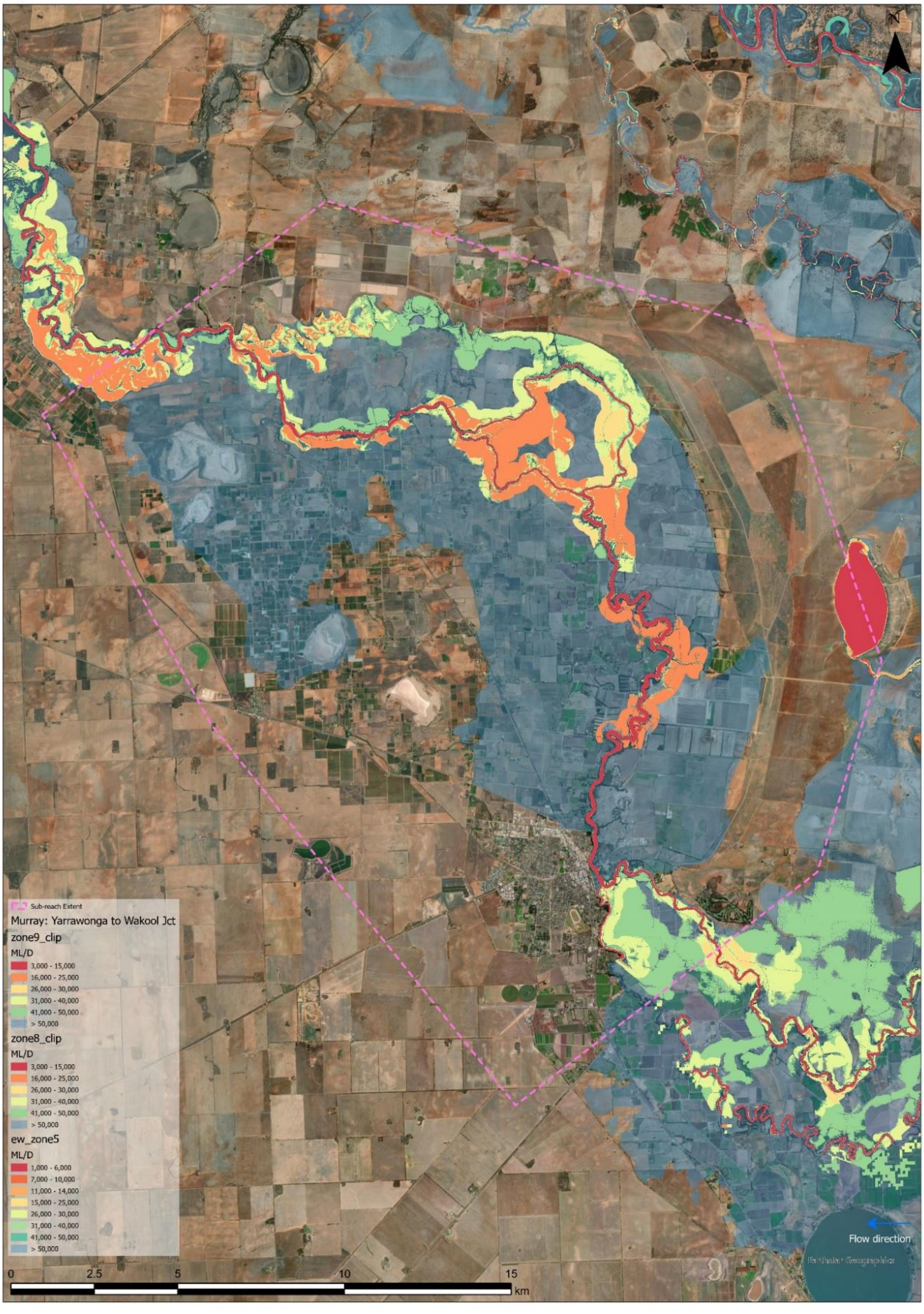

Figure 3 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

4. Base case

The base case geomorphic features and processes are summarised Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (levees)	Deposition
Floodplain (> bankfull connection)	Sediment deposition
Floodplain (wetlands)	Sediment connectivity

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 10 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows:

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Output flow information Wakool Junction have been used for assessing the flow options scenarios.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Levees	Desposition	0	0	2	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Wetlands	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**1.01**	**0.91**	**0.76**	**0.37**	**0.33**
Likelihood (Y45D40 events per year)		1.01	0.93	0.84	0.39	0.31
Likelihood (Y30D30 events per year)		1.01	0.95	0.82	0.38	0.32

The planform of the River Murray channel including the anabranch section appears to be able under base case (current) conditions. Smaller anabranches may be susceptible to avulsion processes under large floodplain flows; however, floodplain flows are highly constrained by levees for these larger events and may not therefore interact with these features limiting their potential to develop further.

In-channel bank erosion may be occurring because of regulated flow conditions but little evidence of specific areas of erosion could be determined from aerial imagery. In-channel features such as bars and benches show periods of accretion and erosion in response to flow conditions in the river.

The future trajectory of this sub-reach is for continued slow rates of geomorphic change such as the potential for bank erosion due to regulated flow conditions. Under the flow options scenarios there is limited change in the flow regime for this sub-reach compared to current constraints and a measurable increase in the rate of change associated with existing geomorphic processes is unlikely to occur.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	6.3	6.4	2%	6.4	2%
Levees	3.6	3.8	4%	3.7	3%
Floodplain (> bankfull)	2.1	2.1	0%	2.1	0%
Wetlands	4.4	4.6	5%	4.6	4%
Average	**4.1**	**4.2**	**3%**	**4.2**	**3%**

6. Limitations

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

The inundation mapping across this sub-reach appears to be buffer to the channel width and may not accurately represent floodplain inundation extents.

7. References

SES (2014). Municipal Flood Emergency Plan – Swan Hill Rural City

OEH (2015) https://www.environment.nsw.gov.au/news/water-at-work-in-speewa-creek

Sub-Reach 11 Geomorphic Outline – Mid Wakool Reach

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The Wakool River is the major southern distributary of the Edward-Wakool River system, branching from the Edward River around 8km downstream of Deniliquin (Tulau & Morand, 2013).

Sub-reach 11 is located on the Wakool River where the river changes from a south-westerly to a more westerly path as it meets the River Murray floodplain. The reach is located just to the north of the Koondrook-Perricoota Forest and includes a number of smaller anabranch channels including Porthole Creek, Merribit Creek, Bookit Creek and Thule Creek. The main flow path from the River Murray to the Wakool River in this sub-reach is via Thule Creek in this sub-reach. Thule Creek is part of the Thule Creek-Green Gully meander plain, the ancestral path of the River Murray prior to the Cadell Fault uplift occurring (Tulau & Morand, 2013).

2. Channel form and processes

a. Anthropogenic changes

There is a regulator on Thule Creek, which diverts flows from the Koondrook Perricoota Forest into the creek. Previously floodplain flows would have made their way from the Koondrook Perricoota Forest to Thule Creek and the Wakool River in this sub-reach but the presence of levees along the Forest margin now limit this occurring. There are also numerous levees along the Wakool River itself in this sub-reach, which appear to limit flows from the Wakool River (via the Edward River) flowing south across the floodplain and connecting to the Koondrook Perricoota Forest.

b. Historic changes based on the historical imagery

There were few observable changes in channel position between historical imagery (circa 1945) and current aerial imagery. At the downstream extent of the reach there appears to minor shifts in channel position which appear to be associated with meander migration. Tullau and Morand (2013) describe how there has been a change in channel morphology over geologic timescales with the youngest fluvial deposits in the Shepparton Formation indicating former river channels that were low sinuosity bedload channels with a very long meander wavelength. More recent paleochannels within the Edward-Wakool systems have a much shorter meander wavelength, are more sinuous and carried a higher proportion of suspended sediment than earlier channels (Tulau & Morand 2013). These more recent paleochannels were formed through incision into the existing alluvial-aeolian Shepparton Formation and are the precursors to the modern channel system (Tulau & Morand 2013).

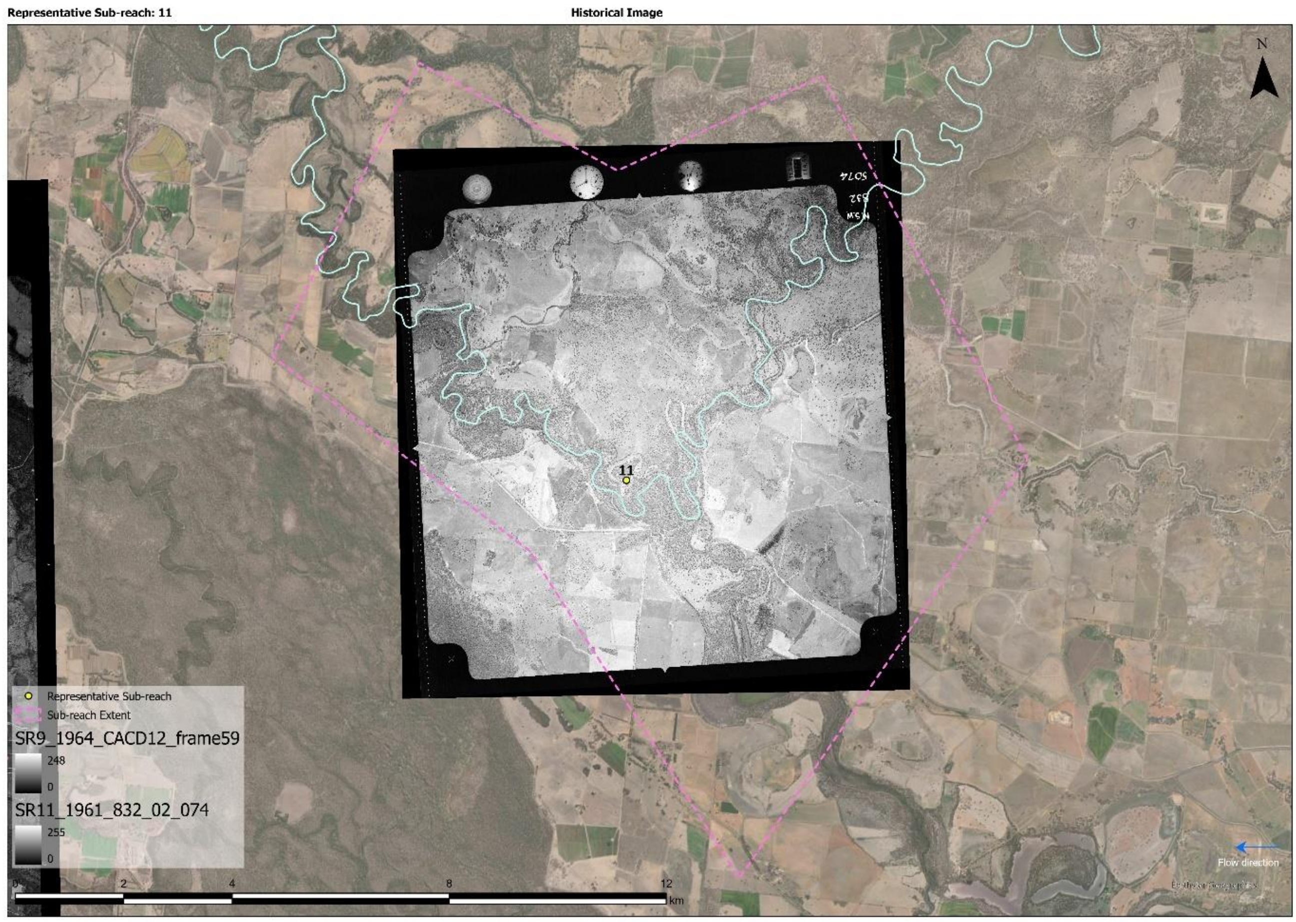

Figure 2 Historic imagery (circa 1964) of the sub-reach extent

c. Forms (mainly based on LiDAR)

The channel in this reach is classified by the Riverstyles Framework as a meandering, fine-grained channel. Towards the downstream extent of the reach, meanders becoming progressively more tortuous. Just upstream of the study reach Yallakool Creek joins the Wakool influencing the morphology within the reach. Downstream of the Yallakool-Wakool junction, the channel is characterised by a large meander wavelength that lies within a broad meander belt (Tulau & Morand 2013). Throughout this reach the banks on the outside bends have been described as steep, up 3 m while the inside banks have been described as approximately 1 m high (Tulau & Morand 2013). The channel width is around 12 m.

Thule Creek joins the Wakool from the south. The channel and adjacent floodplain of Thule Creek lie lower in the floodplain than the current Wakool River. Flows would preferentially move from the Wakool River to Thule Creek due to the natural gradient of the waterways (as seen in the lidar).

d. Processes

There is little evidence of recent large-scale channel change within this sub-reach however the complex interaction of the modern anabranching channels and the paleo-channels across the broad meander belt present a complex system with the potential for both lateral and vertical erosion and deposition. Available information suggests the banks are relatively stable (Talau & Morand, 2013).

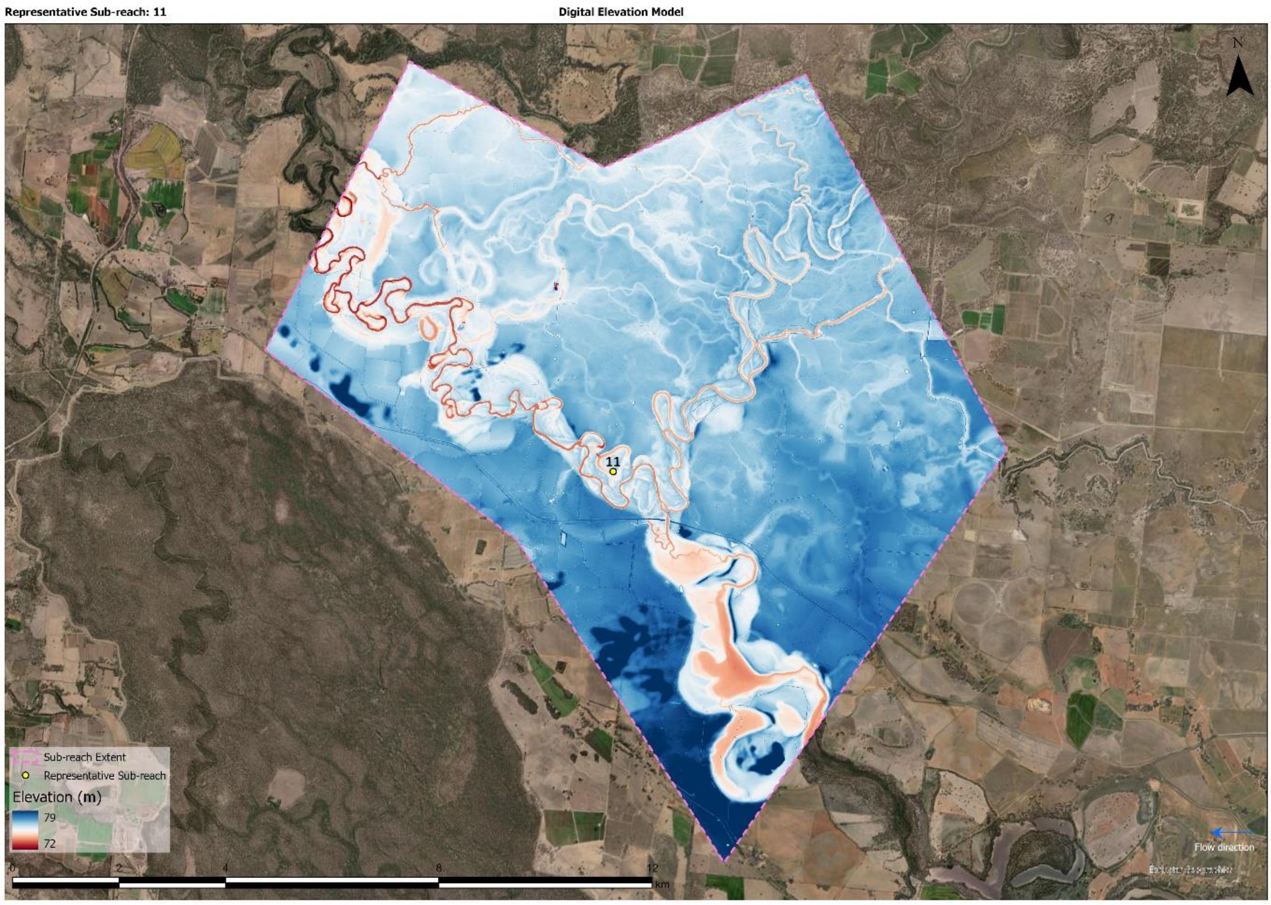

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

3. Floodplain form and process

e. Anthropogenic changes

As noted previously, levees and regulators now control the interaction of floodplain flows from the Wakool River and Thule Creek with the Koondrook-Perricoota Forest.

f. Hydrological connections

Specific to this sub-reach, the Thule Regulator can divert flows from the Koondrook-Perricoota Forest to the Wakool River via Thule Creek or the reach can receive flows from the Yarraman Channel via the Murrumbidgee Irrigation Limited (MIL) Thule escape. Environmental flows have been trialled from the Koondrook-Perricoota Forest to flush carbon and nutrients through Thule Creek into the Wakool River however flow releases via the Thule regulator did not connect to the Wakool due to infiltration into the channel bed as a result of prior dry conditions and being impeded by a low-level road crossing (Watts and Liu, 2020). The natural gradient of Thule Creek may also limit the ability to connect relatively low flows from the Koondrook-Perricoota to the Wakool River as its bed lies lower in the floodplain than the Wakool River. Higher magnitude flood flows would likely overcome this restriction.

Flows from the Wakool River southward into Thule Creek were observed in 2016 (Watts et al 2017).

The channel capacity of the Wakool River is limited to around 1,000-3000 ML/d. Floodplain channels, cutoffs and anabranches together with low-lying floodplain area north of the main Wakool River channel s are engaged from 4,000 to 6,000 ML/d. Flood extents increase further up to 14,000 ML/d and above.

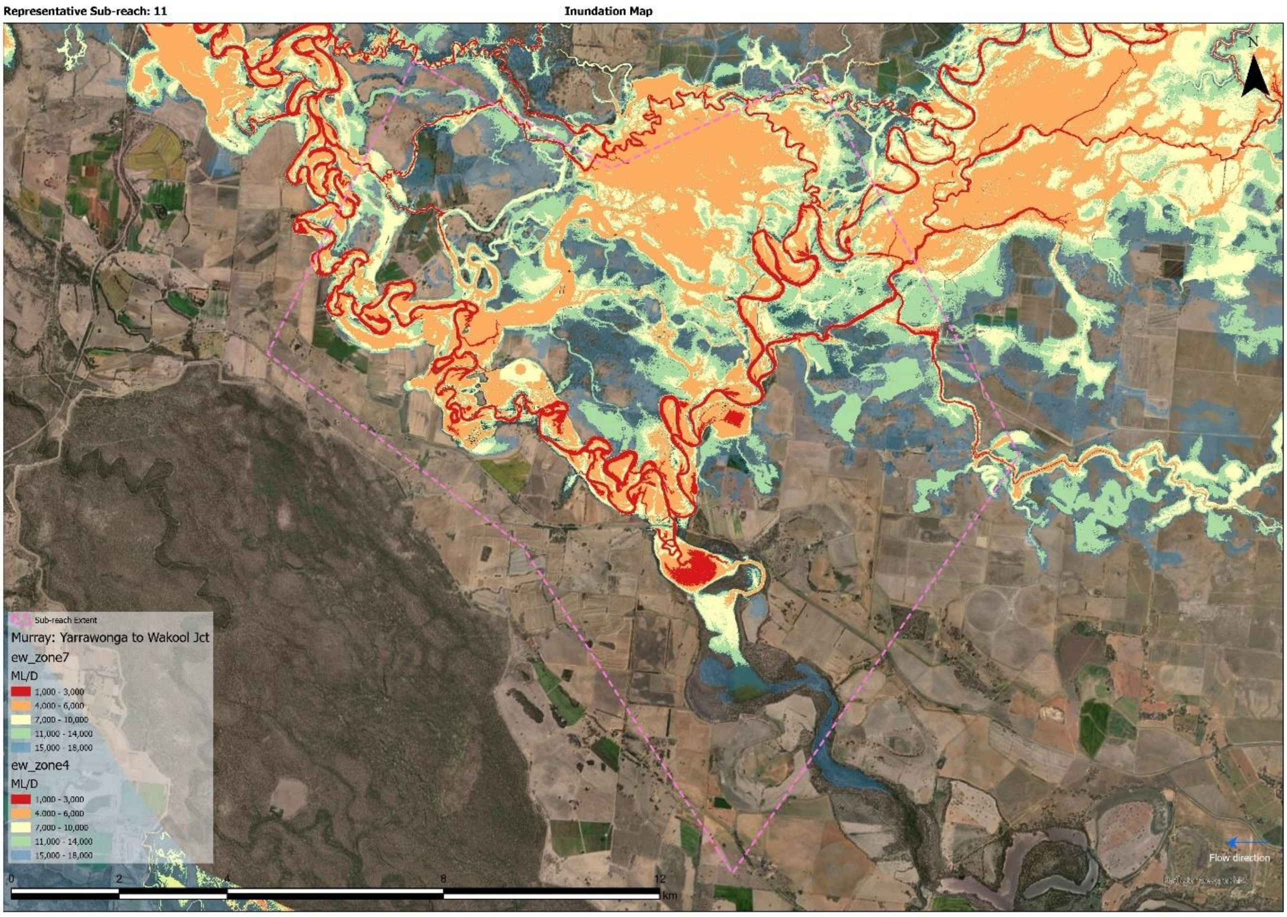

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

g. Form (mainly based on LiDAR)

This reach is characterised by abundant anabranch channels are various stages of development as well a variety of distributary channel forms. At the upstream extent of the reach, Porthole Creek joins the Wakool and just downstream of this, Merribit Creek diverges from the main channel. At the downstream extent of the reach, Bookit Creek, an anabranch of Merribit Creek joins the Wakool River. Across the floodplain along this reach meander cutoffs are abundant, particularly within the downstream extent of the reach. Meander migration and other shifts in channel position are also evident with parts of the reach partly confined within an historic meander belt.

h. Processes

The presence of many channels, floodrunners, scroll bars and billabongs indicates that key processes operating within the reach include avulsion and anabranch development, meander migration and meander cut off. These large, reach scale processes appear to be the dominant processes within the reach however change is slow given the low energy nature of the system. The reach and broader Edward-Wakool system has been described as complex and dynamic with distributary, anabranching, convergent and braided channel patterns evident across the broader floodplain (Tulau & Morand 2013).

4. Base case

The base case geomorphic features and processes are summarised Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition
Floodplain (wetlands / billabongs / distributary channels)	Sediment connectivity

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 11 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This reach of the Wakool River can receive flows from the River Murray via the Koondrook Perricoota (predominantly high flows) or from the Edward River systems.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Flows in the Wakool River are significantly controlled by regulators and weirs. For this flow options assessment, the flow frequency for current constraints and under the flow options for Stony Crossing have been adopted.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Benches	Bench edge erosion	2	2	2	1	1
Cutoffs	Meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**0.67**	**0.52**	**0.46**	**0.37**	**0.36**
Likelihood (Y45D40 events per year)		0.83	0.67	0.57	0.41	0.37
Likelihood (Y30D30 events per year)		0.82	0.56	0.48	0.38	0.36

The sub-reach and broader Edward-Wakool system has been described as complex and dynamic with distributary, anabranching, convergent and braided channel patterns evident across the broader floodplain (Tulau & Morand 2013). There is little evidence of significant active channel or floodplain erosion or aggradation processes likely in part due to the regulated nature of flows through the system. Natural floodplain flows from the River Murray via the Koondrook Pericoota Forest has been restricted by levees and regulators and flows into the Wakool system from the Edward River are themselves highly regulated.

The dominant geomorphic processes under the base case for this sub-reach is likely to be riverbank erosion as a result of prolonged constant flow conditions. Under the flow options scenarios most of the change in the flow regime for this sub-reach compared is in the small fresh category although there is also change to bankfull and moderate bankfull flows under the higher Y45D40 option which may increase current low rates of change.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	4.3	5.2	22%	4.8	13%
Benches	4.0	4.9	22%	4.5	10%
Cutoffs	5.3	6.2	18%	5.6	6%
Anabranches / Floodrunners (sub-bankfull)	4.6	5.4	17%	4.8	4%
Floodplain (> bankfull)	2.2	2.3	8%	2.2	2%
Anabranches / Floodrunners (> bankfull)	2.2	2.3	8%	2.2	2%
Wetlands, billabongs, distributary channels	3.6	4.0	14%	3.7	3%
Average	**3.7**	**4.4**	**17%**	**4.0**	**6%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Tulau, M & Morand, D. 2013. *Aspects of Quaternary geology, geomorphic history, stratigraphy, soils and hydrogeology in the Edward-Wakool channel system with particular reference to the distribution of sulfidic channel sediments.* Report prepared by Office of Environment and Heritage for Southern Cross Geoscience, Southern Cross University and the Murray Darling Basin Authority.

Watts, R., & Liu, X. (2020). Monitoring an environmental watering action in Thule Creek to evaluate the contribution of flow via Thule Creek to the productivity of the Wakool River. Institute for Land, Water and Society.

GHD (2010). Koondrook Perricoota Forest Flood Enhancement Project, report for the Living Murray Initiative

Watts RJ, Wolfenden B, Howitt JA, Jenkins K, McCasker N, Blakey R (2017). 'Contribution of Koondrook-Perricoota floodplain runoff to the productivity of the Wakool River'. Report prepared for Forestry Corporation of New South Wales

Sub-Reach 12 Geomorphic Outline – Werai Reach

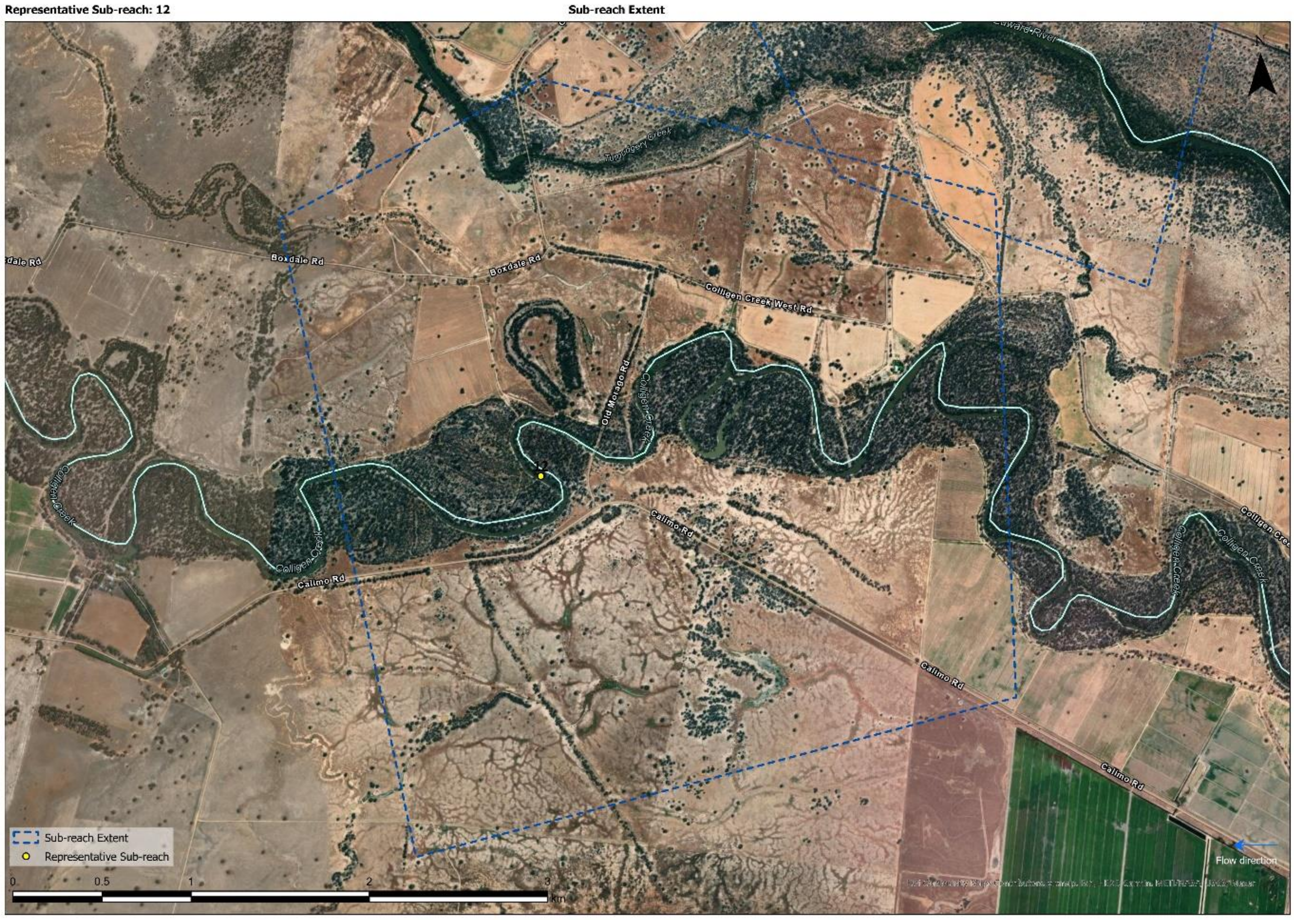

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The sub-reach is on Colligen Creek, a major anabranch of the Edward-Kolety River, 10 km west of where the two waterways branch (near Stevens Weir). Colligen Creek is the major channel of the two, with a broad, complex meander belt with numerous ox-bow cutoff meanders, in contrast to the Edward, which lacks such in this section (Tulau & Morand 2013).

The main flow regulating structures within the Edward-Kolety-Wakool system are the Gulpa Creek Offtake, Edward-Kolety River Offtake (both located on the Murray River), and Stevens Weir, located on the Edward-Kolety River downstream of Colligen Creek. The Stevens Weir creates a weir pool that allows water to be delivered to Colligen Creek and other waterways of the Edward-Kolety-Wakool system. Water diverted into the Mulwala Canal from Lake Mulwala can also be delivered into the Edward-Kolety-Wakool system through 'escapes' or outfalls managed by the irrigator-owned company Murray Irrigation Limited (Watts et al. 2020).

2. Channel form and processes

a. Anthropogenic changes

The key changes that have impacted on the reach are those associated major changes in the broader Edward-Kolety-Wakool system (and the Murray Darling in general). These changes include altered hydrology through the construction of dams and storages, flow diversion for irrigation and the associated infrastructure (weirs, diversion channels etc.) and desnagging of channels that was undertaken to improve flow conveyance and navigability.

Locally the main change for this sub-reach is the construction of Stevens Weir and regulation of the natural flow regime into the waterway.

b. Historic changes based on the historical imagery

There were few observable changes in channel position between the 1970 back and white aerial photographs and the 2021 Maxar satellite imagery, aside from some signs of potential channel widening on the outside of meander bends. The resolution of the historic imagery does now allow for an assessment of instream wood loads or bar forms.

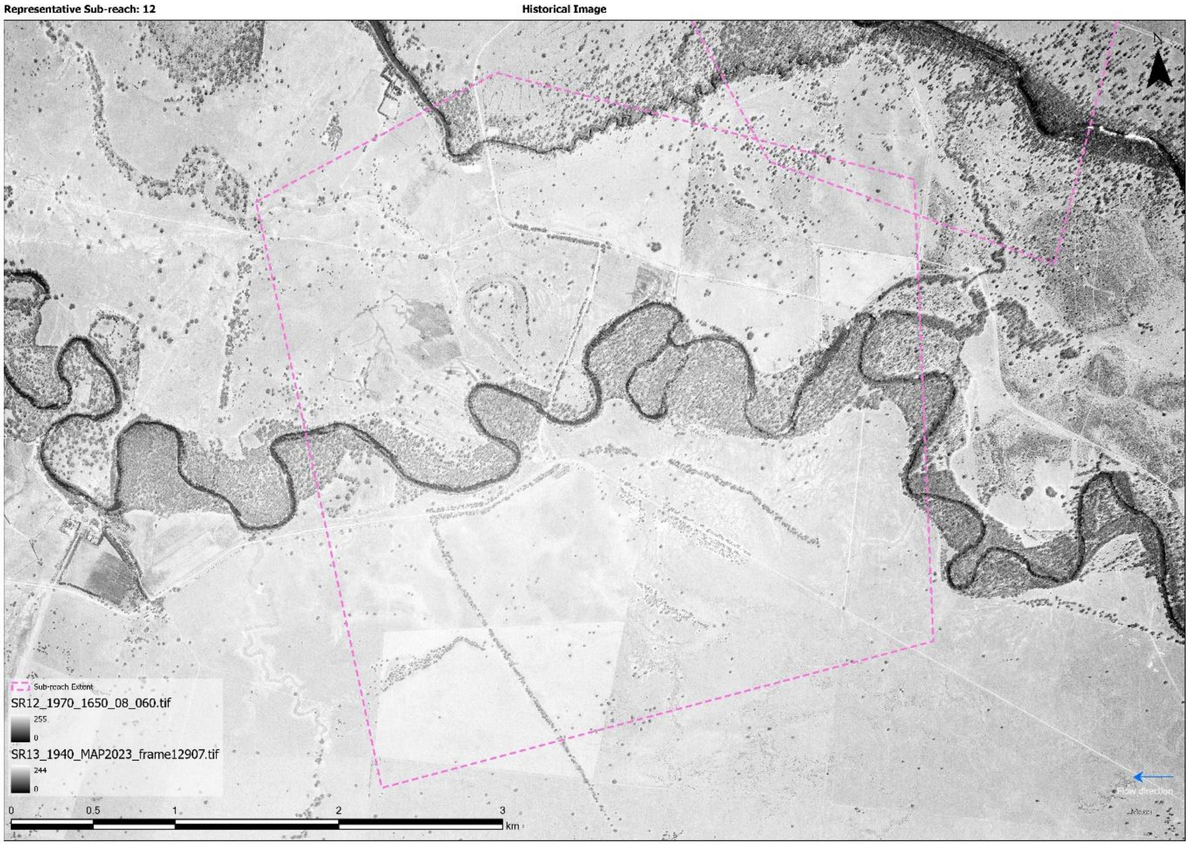

Figure 2 Historic imagery (circa 1970) of the sub-reach extent

c. Forms (mainly based on LiDAR)

Colligen Creek is described as a laterally unconfined, continuous channel, meandering, with a fine-grained bed in the RiverStyles data. There are no sub-bankfull connections to the floodplain in the sub-reach. There are two meander cut-offs within the sub-reach and one oxbow lake.

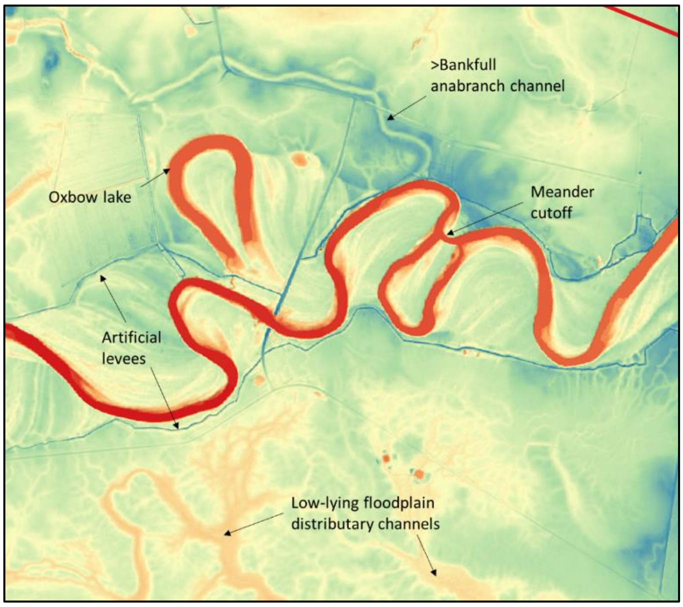

Figure 3 Example lidar view of the sub-reach showing key forms.

d. Processes

The dominant processes affecting channel form in the Edward/Kolety-Wakool system is likely related to the changes in discharge brought by regulation. High flows during summer (when they would normally be low) can cause erosion and hamper vegetation recruitment and growth, typically leading to a decline in bank condition and ultimately channel widening. However, limited data is available for Colligen Creek specifically. At a single location surveyed using photogrammetry over a year, minimal change was detected (Watts et al. 2020).

3. Floodplain form and process

e. Anthropogenic changes

The key anthropogenic changes to the floodplain area include land clearing outside the ~500 m wide meander belt, the construction of levees and the installation of Stevens Weir. The majority of main channel in the sub-reach is bounded by artificial levees on either side of the meander belt, which confines the floodplain width to 300-700 m, isolating most floodplain channels.

f. Hydrological connections

Flows in this reach are regulated by the level at Stevens Weir. Connection to the floodplain within the sub-reach is largely restricted to the meander belt, with artificial levees preventing wider connectivity. Flows below 26,000 ML/d are largely confined to the channel itself in this sub-reach.

Downstream of the sub-reach Colligen Creek is the key source of water for the Werai Forest. The creek is normally operated at 170 ML/d in summer, and above 800–850 ML/d water spills into lagoons and creek runners, which has been historically avoided to minimise losses when supplying regulated flow.

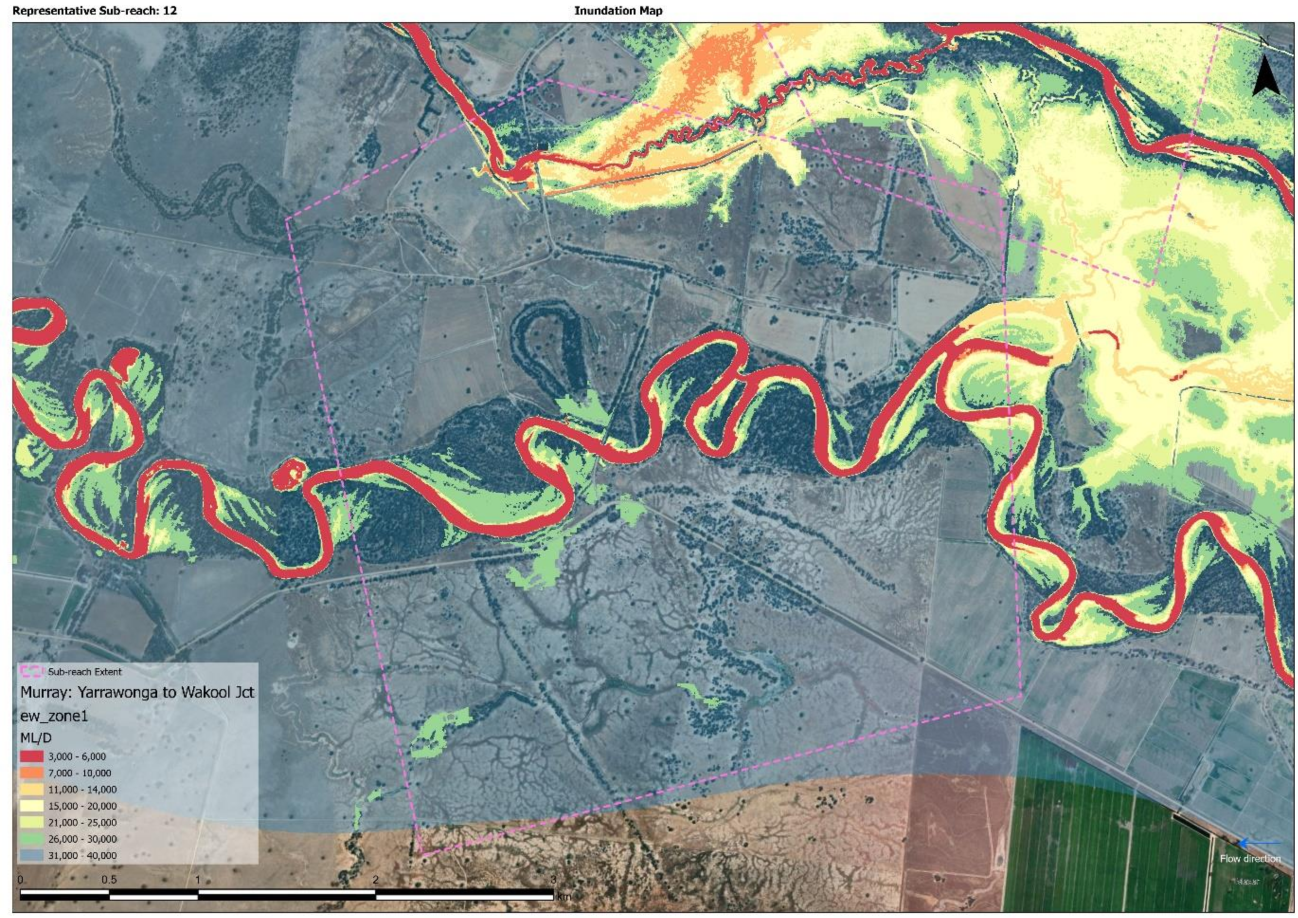

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

g. Form (mainly based on LiDAR)

The floodplain around the sub-reach is characterised by low-lying areas that would have been connected to the main channel by >bankfull distributary and anabranch channels, along with several meander cut-offs, and an oxbow lake. Floodplain channels in the sub-reach are now largely disconnected from the channel by constructed levees.

Figure 5 Lidar imagery of the sub-reach showing the different geomorphic features present

a. Processes

The processes of erosion and deposition on the floodplain are a balance between the length and rate of flow, the sediment volumes delivered in the flows and the vegetation. Infrequent inundation (due to the highly regulated nature of the system) mean that rates of change will be low. Artificial levees will also act to constrain where deposition and erosion will occur during >bankfull events.

Bank erosion processes close to the connection with Stevens Weir are likely to be affected by weir operations, with sudden changes in water levels potentially triggering slumping of the banks. This process was investigated in detail as a part of the CEWO MER project for the Edward/Kolety-Wakool in 2019-20. While the single Colligen Creek site surveyed as a part of the MER project showed minimal erosion, this was not typical of the findings for the system in general. It was found that prolonged operational flows prepared the bank for erosion by steepening and notching and leaving the upper bank to dry. Subsequent higher environmental or unregulated flows inundated the bank above the notch, leaving a large mass of unsupported, saturated soil prone to mass failure following the flow recession (Watts et al. 2020).

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 12 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This reach receives flows from the Edward River systems via the River Murray.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Flows from the Edward River are most likely to be influenced by the flow option scenarios and therefore these flows have been applied in the analysis based on the results for Steven's Weir.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Benches	Bench edge erosion	2	2	2	1	1
Cutoffs	Meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**0.98**	**0.69**	**0.49**	**0.29**	**0.16**
Likelihood (Y45D40 events per year)		0.99	0.85	0.66	0.26	0.15
Likelihood (Y30D30 events per year)		0.98	0.85	0.46	0.28	0.15

Under the base case, it is likely that prolonged, constant high summer flows will result in the loss of vegetation from the lower banks of these waterways, reducing the ability of these banks to withstand future peaked or prolonged flow events. Without vegetation on these lower banks, it is likely that further steepening and slumping will occur, facilitating a positive feedback loop exacerbating this cycle (Watts et al. 2020). The prolonged constant flow processes most influencing geomorphic processes affecting this sub-reach are common to the broader Edward-Kolety-Wakool system.

Under the flow options scenarios there is some change in the flow regime for this sub-reach compared to current constraints in the large fresh and bankfull flow categories which may increase current rates of change. Those locations closest to offtakes or regulators which experience more rapid changes in flow levels are likely to be the most susceptible to change and any potential increase in the rate of change as a result of the flow options scenarios.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.3	5.7	9%	5.5	5%
Benches	4.8	5.4	13%	5.0	5%
Cutoffs	5.2	5.9	13%	5.4	3%
Anabranches / Floodrunners (sub-bankfull)	4.2	4.9	16%	4.4	4%
Floodplain (> bankfull)	1.4	1.2	-11%	1.3	-5%
Anabranches / Floodrunners (> bankfull)	1.4	1.2	-11%	1.3	-5%
Average	**3.7**	**4.1**	**10%**	**3.8**	**3%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes. Specific geomorphic data on this sub-reach is limited and therefore inferences have been made based on what is known about the broader Edward/Kolety-Wakool system of which Colligen Creek is a part.

7. References

Tulau, M & Morand, D. 2013. *Aspects of Quaternary geology, geomorphic history, stratigraphy, soils and hydrogeology in the Edward-Wakool channel system with particular reference to the distribution of sulfidic channel sediments.* Report prepared by Office of Environment and Heritage for Southern Cross geoscience, Southern Cross University and the Murray Darling Basin Authority.

Watts R.J., Bond N.R, Healy S., Liu X., McCasker N.G., Siebers A., Sutton N., Thiem J.D., Trethewie J.A., Vietz G., Wright D.W. (2020). *Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project: Edward/Kolety-Wakool River System Selected Area Technical Report, 2019-20*. Report prepared for Commonwealth Environmental Water Office.

Sub-Reach 13 Geomorphic Outline – Werai Reach

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The sub-reach is on the Edward/Kolety River, a major anabranch of the Edward/Kolety-Wakool system, 10 km downstream of Stevens Weir, at the boundary of the Werai Forest. The sub-reach includes upstream end of the Tumudgery Creek anabranch, a distributary that supplies water to the Werai Forest. The broader Edward/Kolety-Wakool system, of which this sub-reach is a part, is a distributary system comprised of a complex network of billabongs, lagoons, depressions, creeks, floodrunners and lakes (Green 2000).

The main flow regulating structure for this sub-reach is the Stevens Weir, which creates a weir pool that allows water to be delivered to the Edward River downstream as well as Colligen Creek and other waterways from the weir pool itself. Water diverted into the Mulwala Canal from Lake Mulwala can also be delivered into the

Edward/Kolety-Wakool system through ‘escapes’ or outfalls managed by the irrigator-owned company Murray Irrigation Limited (Watts et al. 2020).

2. Channel form and processes

a. Anthropogenic changes

The key changes that have impacted on the reach include altered hydrology through the construction of dams and storages, flow diversion for irrigation and the associated infrastructure (weirs, diversion channels etc.). Examples in this sub-reach include the construction of the Tumudgery Creek regulator, which acts to contain flow within the main Edward/Kolety channel, and the Dahwilly No. 5 escape, which supplies water to surrounding land for irrigation. Desnagging of channels also likely occurred in the past to improve flow conveyance and navigability.

b. Historic changes based on the historical imagery

There were no observable changes in channel position in this section of the Edward/Kolety River between either the 1940 or 1970 black and white aerial photographs and the 2021 Maxar satellite imagery. There has been an increase in the extent and density of riparian and floodplain canopy cover since 1970. The resolution of the historic imagery does now allow for an assessment of instream wood loads or bar forms.

c. Forms (mainly based on LiDAR)

This section of the Edward/Kolety River is described in the RiverStyles data as a laterally unconfined, continuous channel with a fine-grained bed. In the upstream half of the sub-reach the channel has low sinuosity, in contrast to the meandering form downstream (beginning where it meets the Werai Forest).

There are two named sub-bankfull connections to the floodplain (Tumudgery Creek and Dahwilly No. 5 escape), both of which are regulated to control outfows. There are also multiple >bankfull distributary channels within the sub-reach that are engaged starting at 7,000 ML/d (see inundation map). One of these distributaries flows into the easter edge of the Werai Forest. There is also one meander cut-off.

Representative Sub-reach: 13 | Historical Image

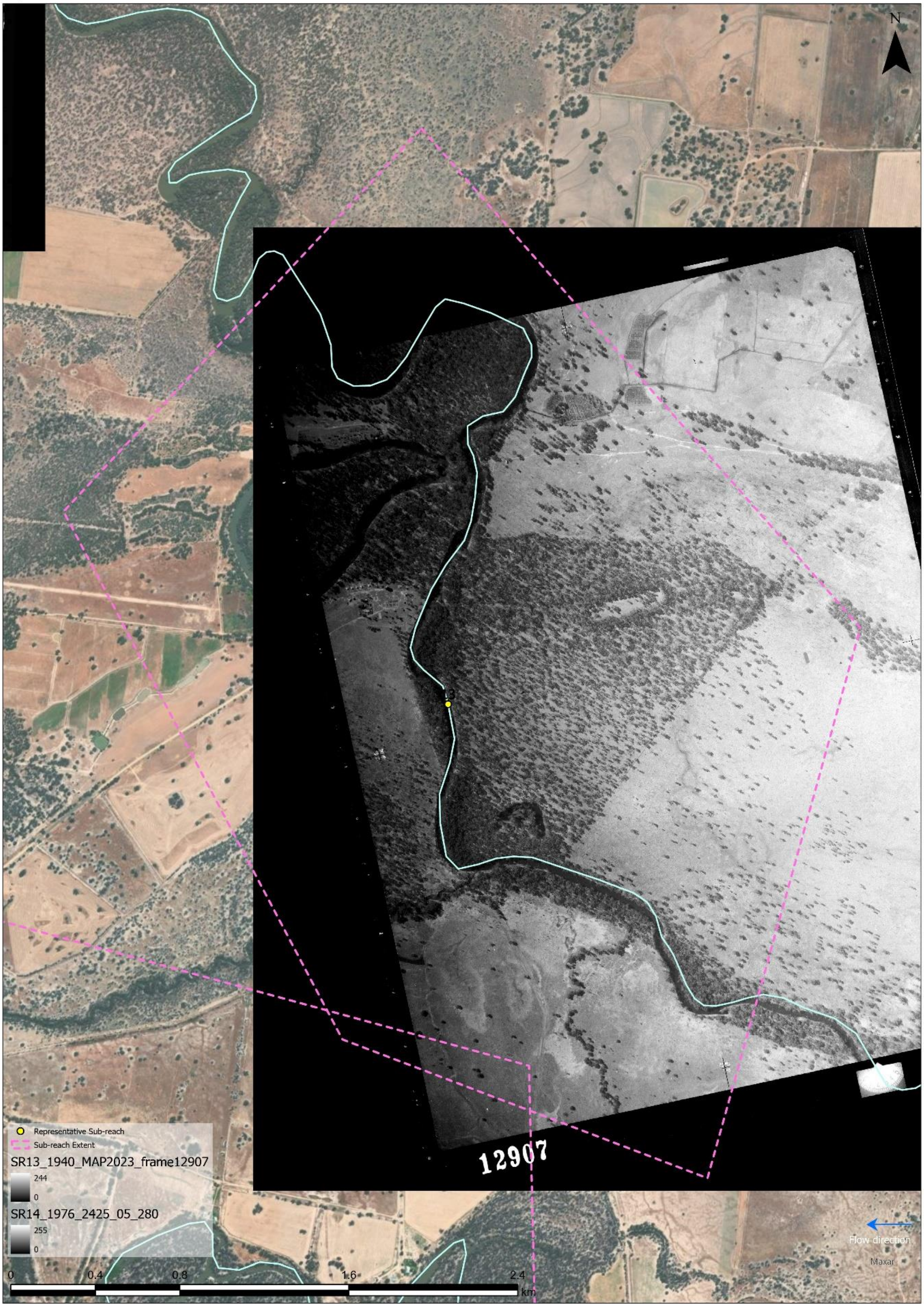

Figure 2 Historic imagery (circa 1976) of the sub-reach extent

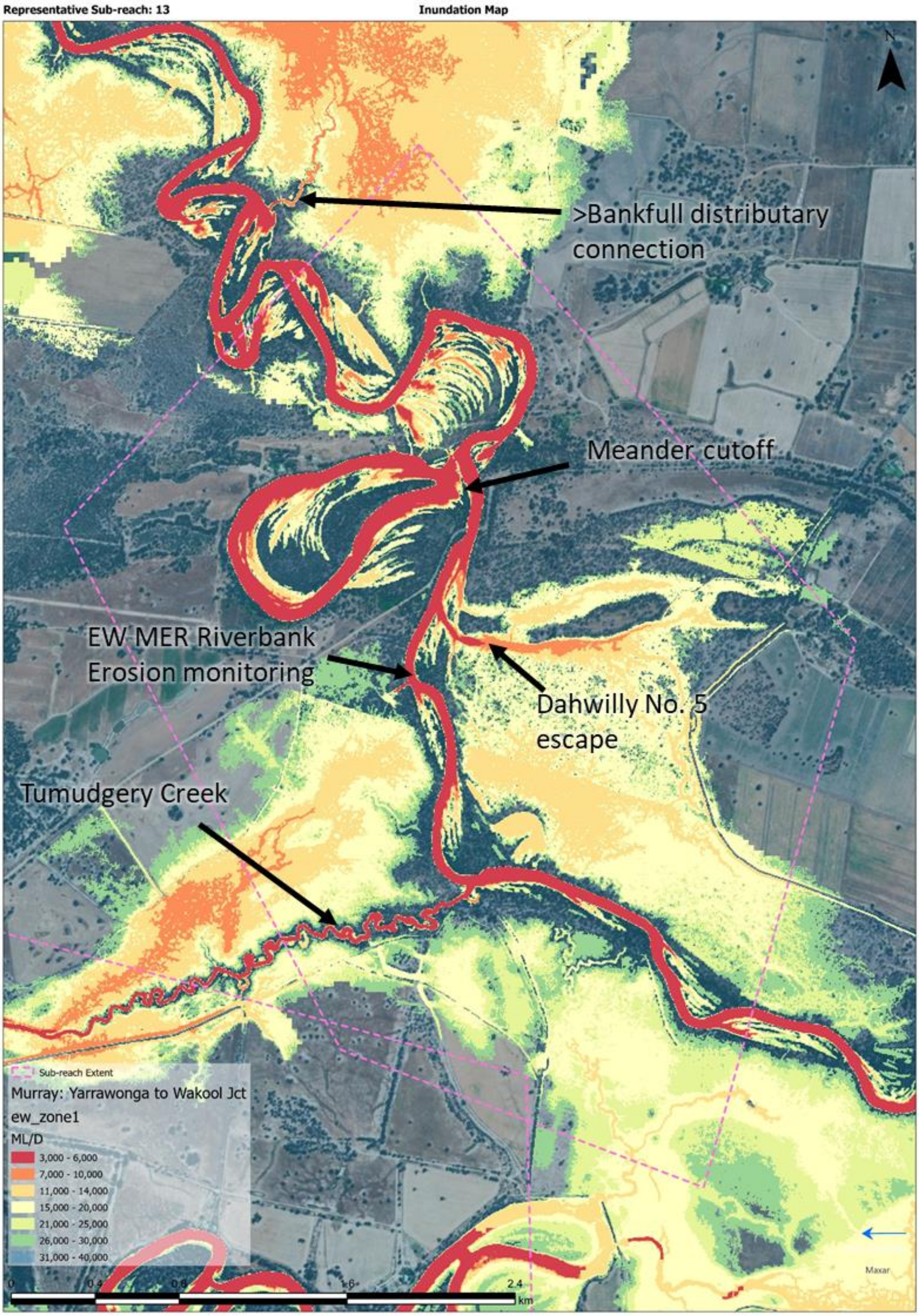

Figure 3 Example lidar view of the sub-reach showing key forms.

d. Processes

The dominant processes affecting channel form in the Edward/Kolety-Wakool system is related to the changes in discharge brought by regulation. High flows during summer (when they would normally be low) can cause erosion and hamper vegetation recruitment and growth, typically leading to a decline in bank condition and ultimately channel widening.

One riverbank section in the sub-reach was assessed in detail as a part of the CEWO MER project for the Edward/Kolety-Wakool in 2019-20. Downstream of Stevens Weir there is a deep notch in bank that corresponds with the prolonged invariable operational flow of around 2500 ML/day. The duration of inundation above the notch and drawdown speed of flow events were found to have a critical influence on the amount erosion from mass-failure events. Prolonged operational flows prepared the bank for erosion by creating a deep notch and leaving the upper bank to dry. Subsequent higher environmental or unregulated flows inundated the bank above the notch, leaving a large mass of unsupported, saturated soil prone to mass failure following the flow recession (Watts et al. 2020).

3. Floodplain form and process

e. Anthropogenic changes

The key anthropogenic changes to the floodplain area include land clearing, however, there has been a more recent increase in the extent and density of riparian and floodplain forest cover, at least since the 1970 historic imagery as captured. Artificial levees have also been constructed alongside the main channel in places, although coverage is not uniform across the sub-reach. The construction of the Dahwilly No. 5 escape to deliver irrigation water to the floodplain is another key change.

f. Hydrological connections

Connection to the floodplain within the sub-reach is via distributary channels from the main Edward/Kolety River and the Tumudgery anabranch. The Dahwilly No. 5 escape also provides flow connection to the floodplain during >bankfull flows. Critically, there is a major distributary connection to the eastern parts of the Werai Forest, just beyond the northern boundary of the sub-reach (see Figure 1).

Inundation mapping shows floodplain inundation commencing around 10,000 ML/d.

g. Form (mainly based on LiDAR)

The floodplain around the sub-reach is characterised by distributary channels, meander cut-offs, and oxbow lakes. Some of the floodplain channels in the sub-reach are now partially disconnected from the channel by constructed levees.

h. Processes

The processes of erosion and deposition on the floodplain are a balance between the length and rate of flow, the sediment volumes delivered in the flows and the vegetation. Infrequent inundation (due to the highly regulated nature of the system) mean that rates of change will be low. Artificial levees will also act to constrain where deposition and erosion will occur during >bankfull events.

Representative Sub-reach: 13 **Inundation Map**

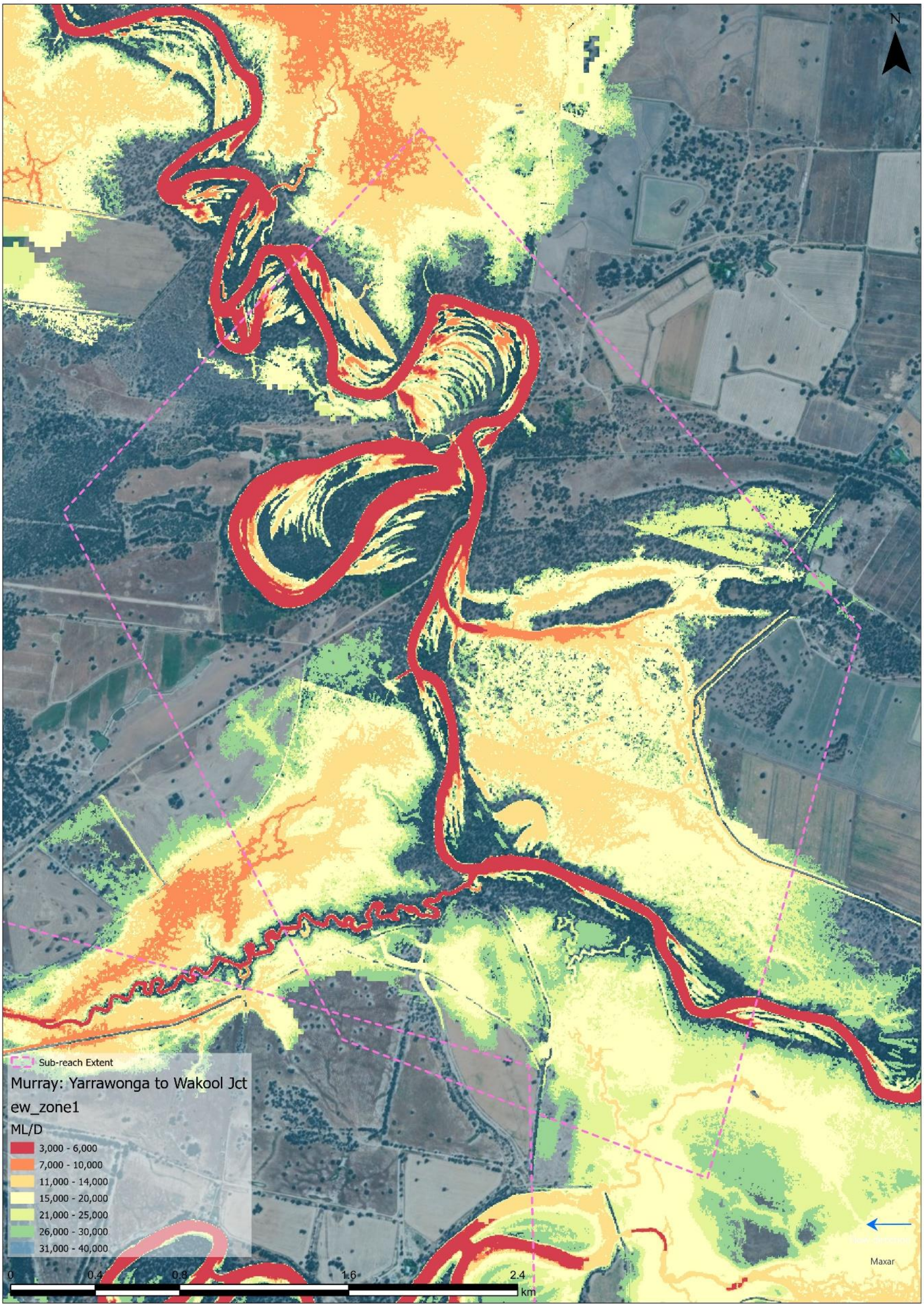

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

4. Base case

The base case geomorphic features and processes are summarised in Table 1

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 13 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This reach receives flows from the Edward River systems via the River Murray.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Flows from the Edward River are most likely to be influenced by the flow option scenarios and therefore these flows have been applied in the analysis based on the results for Steven's Weir.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Benches	Bench edge erosion	2	2	2	1	1
Cutoffs	Meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**0.98**	**0.69**	**0.49**	**0.29**	**0.16**
Likelihood (Y45D40 events per year)		0.99	0.85	0.66	0.26	0.15
Likelihood (Y30D30 events per year)		0.98	0.85	0.46	0.28	0.15

Under the base case, it is likely that prolonged, regulated high summer flows will result in the loss of vegetation from the lower banks of these waterways, reducing the ability of these banks to withstand future peaked or prolonged flow events. Without vegetation on these lower banks, it is likely that further steepening and slumping will occur, facilitating a positive feedback loop exacerbating this cycle (Watts et al. 2020). The prolonged constant flow processes most influencing geomorphic processes affecting this sub-reach are common to the broader Edward-Kolety-Wakool system.

Under the flow options scenarios there is some change in the flow regime for this sub-reach compared to current constraints in the large fresh and bankfull flow categories which may increase current rates of change. Those locations closest to offtakes or regulators which experience more rapid changes in flow levels are likely to be the most susceptible to change and any potential increase in the rate of change as a result of the flow options scenario.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.3	5.7	9%	5.5	5%
Benches	4.8	5.4	13%	5.0	5%
Cutoffs	5.2	5.9	13%	5.4	3%
Anabranches / Floodrunners (sub-bankfull)	4.2	4.9	16%	4.4	4%
Floodplain (> bankfull)	1.4	1.2	-11%	1.3	-5%
Anabranches / Floodrunners (> bankfull)	1.4	1.2	-11%	1.3	-5%
Average	**3.7**	**4.1**	**10%**	**3.8**	**3%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes. There is limited sub-reach specific data on channel form and processes. Therefore, inferences have been made based on site-specific data (e.g., from the CEWO MER project) and what is known about the broader Edward/Kolety-Wakool system of which this sub-reach is a part.

7. References

Green, Damian. (2000). *The Edward/Wakool system: River regulation and environmental flows*. Report prepared for the Department of Land and Water Conservation, Murray Region, Deniliquin.

Tulau, M & Morand, D. (2013). *Aspects of Quaternary geology, geomorphic history, stratigraphy, soils and hydrogeology in the Edward-Wakool channel system with particular reference to the distribution of sulfidic channel sediments.* Report prepared by Office of Environment and Heritage for Southern Cross geoscience, Southern Cross University and the Murray Darling Basin Authority.

Watts R.J., Bond N.R, Healy S., Liu X., McCasker N.G., Siebers A., Sutton N., Thiem J.D., Trethewie J.A., Vietz G., Wright D.W. (2020). *Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project: Edward/Kolety-Wakool River System Selected Area Technical Report, 2019-20*. Report prepared for Commonwealth Environmental Water Office.

Sub-Reach 14 Geomorphic Outline – Werai / Mid Edward Reaches

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The sub-reach is within the Edward/Kolety-Wakool system, focussed on the Edward/Kolety River and Colligen Creek, where they converge within the Werai Forest, 30 km downstream of Steven's Weir. The Werai Forest is a highly complex distributary system comprised of a network of anabranches, wetlands, billabongs, lagoons, depressions, lakes, creeks, and floodrunners (Green 2000).

The main flow regulating structure for this sub-reach is the Stevens Weir, which creates a weir pool that allows Commonwealth environmental water to be delivered to Colligen Creek and other waterways of the

Edward/Kolety-Wakool system. Water diverted into the Mulwala Canal from Lake Mulwala can also be delivered into the Edward/Kolety-Wakool system through 'escapes' or outfalls managed by the irrigator-owned company Murray Irrigation Limited (Watts et al. 2020).

2. Channel form and processes

a. Anthropogenic changes

The key changes that have impacted on the reach include altered hydrology through the construction of dams and storages, flow diversion for irrigation and the associated infrastructure (weirs, diversion channels etc.). Desnagging of channels also likely occurred in the past to improve flow conveyance and navigability.

b. Historic changes based on the historical imagery

There were no observable changes in channel position in this section of the Edward/Kolety River or Colligen Creek between the 1976 black and white aerial photographs and the 2021 Maxar satellite imagery. The resolution of the historic imagery does now allow for an assessment of instream wood loads or bar forms.

c. Forms (mainly based on LiDAR)

The section of the Edward/Kolety River and Colligen Creek in this sub-reach are described in the RiverStyles data as a laterally unconfined, continuous meandering channel with a fine-grained bed. The area is characterised by a highly complex network of anabranching, distributary and converging channels. There are multiple sub-bankfull connections from both waterways that would deliver water to the wetlands and flood runners of the Werai Forest (Figure 1) and many >bankfull connections. There are also meander cutoffs and oxbow lakes.

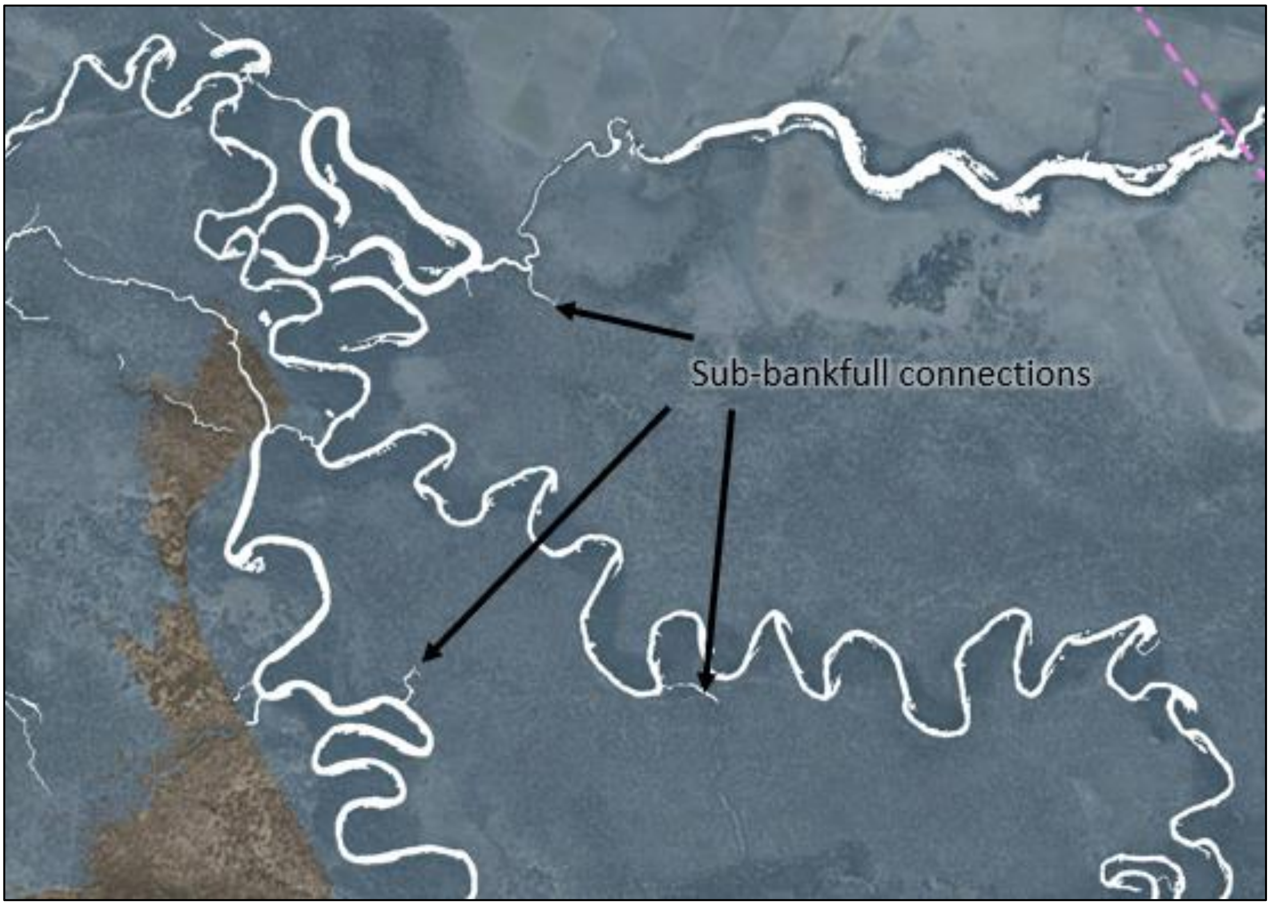

Figure 2 Map of part of sub-reach 14 (where the Edward/Kolety River and Colligen Creek converge) showing sub-bankfull connections. White areas denote inundation under bankfull conditions.

a. Processes

The dominant processes affecting channel form in the Edward/Kolety-Wakool system are related to the changes in discharge brought by regulation. High flows during summer (when they would normally be low) can cause erosion and hamper vegetation recruitment and growth, typically leading to a decline in bank condition and ultimately channel widening.

One riverbank section in the sub-reach was assessed in detail as a part of the CEWO MER project for the Edward/Kolety-Wakool in 2019-20. Downstream of Stevens Weir there is a deep notch in bank that corresponds with the prolonged invariable operational flow of around 2500 ML/day. The duration of inundation above the notch and drawdown speed of flow events were found to have a critical influence on the amount erosion from mass-failure events. Prolonged operational flows prepared the bank for erosion by creating a deep notch and leaving the upper bank to dry. Subsequent higher environmental or unregulated flows inundated the bank above the notch, leaving a large mass of unsupported, saturated soil prone to mass failure following the flow recession (Watts et al. 2020).

Representative Sub-reach: 14 **Inundation Map**

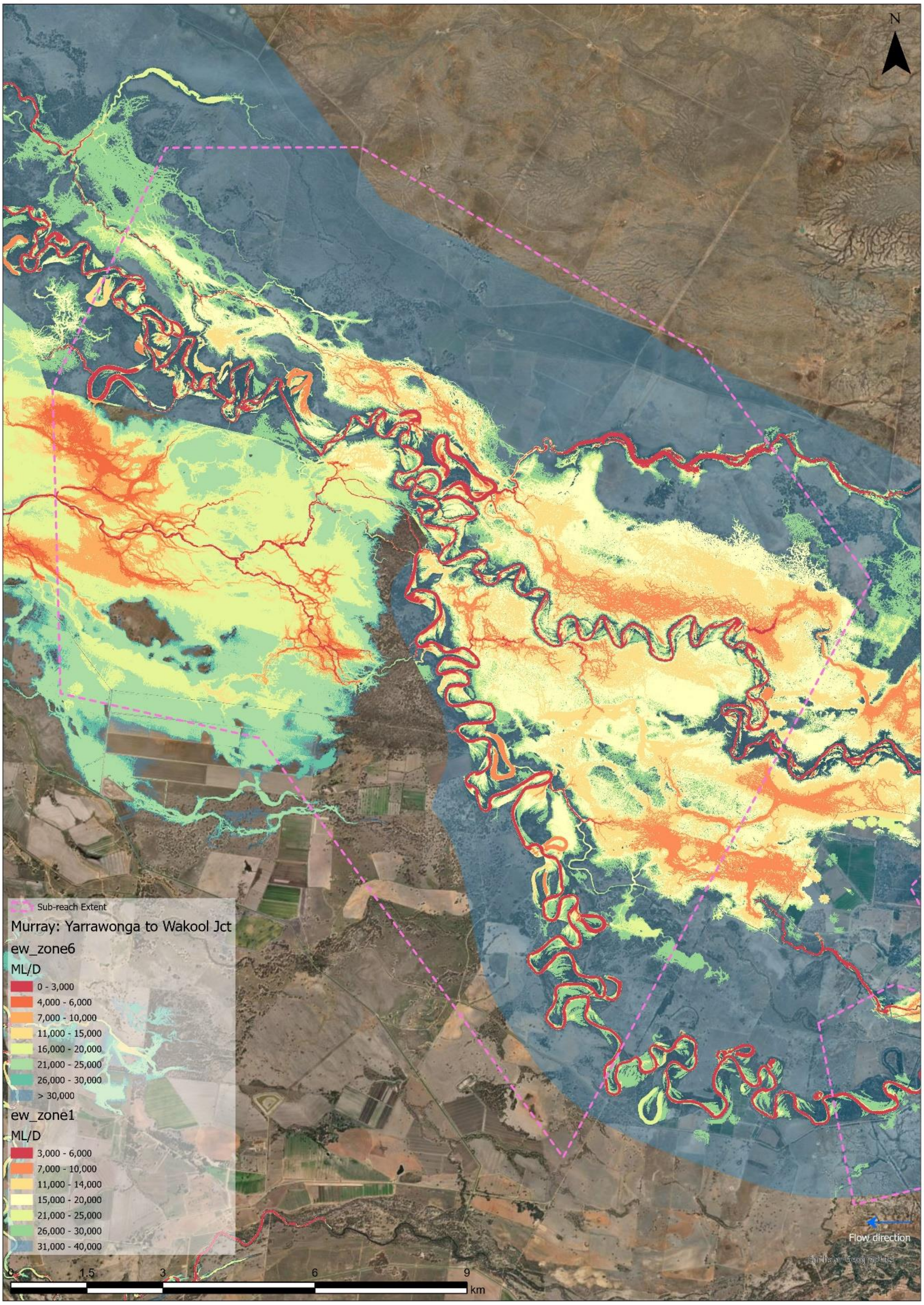

Figure 3 Inundation map of sub-reach 14 showing the highly complex network of distributary channels that characterise the Werai Forest.

3. Floodplain form and process

b. Anthropogenic changes

The key anthropogenic changes to the floodplain area include land clearing outside the Werai Forest. Artificial levees have also been constructed in places, although mostly outside the forest.

c. Hydrological connections

The Werai Forest is a distributary wetland system that is characterised by a very high degree of channel-floodplain connection. Connection is via both sub-bankfull and >bankfull distributary channels and a highly complex network of floodrunners within the forest. However, flow regulation, intended to maximise conveyance of water downstream, reduces the frequency of inundation compared to natural conditions.

d. Form (mainly based on LiDAR)

The floodplain around the sub-reach is characterised by distributary channels, meander cut-offs, and oxbow lakes.

e. Processes

The processes of erosion and deposition on the floodplain are a balance between the length and rate of flow, the sediment volumes delivered in the flows and the vegetation. Infrequent inundation (due to the highly regulated nature of the system) mean that rates of change will be low. Artificial levees will also act to constrain where deposition and erosion will occur during >bankfull events.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition
Wetlands, Billabongs, Distributaries	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 14 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This reach receives flows from the Edward River systems via the River Murray.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Flows from the Edward River are most likely to be influenced by the flow option scenarios and therefore these flows have been applied in the analysis based on the results for Steven's Weir.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Benches	Bench edge erosion	2	2	2	1	1
Cutoffs	Meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**0.98**	**0.69**	**0.49**	**0.29**	**0.16**
Likelihood (Y45D40 events per year)		0.99	0.85	0.66	0.26	0.15
Likelihood (Y30D30 events per year)		0.98	0.85	0.46	0.28	0.15

Under the base case, it is likely that prolonged, regulated high summer flows will result in the loss of vegetation from the lower banks of these waterways, reducing the ability of these banks to withstand future peaked or prolonged flow events. Without vegetation on these lower banks, it is likely that further steepening and slumping will occur, facilitating a positive feedback loop exacerbating this cycle (Watts et al. 2020).

The prolonged constant flow processes most influencing geomorphic processes affecting this sub-reach are common to the broader Edward-Kolety-Wakool system. However, other processes relevant to a distributary river system as occurs here at Werai are also occurring (meander migration, avulsion development, floodplain sediment deposition).

Under the flow options scenarios there is some changes in the flow regime for this sub-reach compared to current constraints in the large fresh and bankfull flow categories which may increase current rates of change. Those locations closest to offtakes or regulators which experience more rapid changes in flow levels are likely to be the most susceptible to change and any potential increase in the rate of change as a result of the flow options scenarios.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Riverbanks	5.3	5.7	9%	5.5	5%
Benches	4.8	5.4	13%	5.0	5%
Cutoffs	5.2	5.9	13%	5.4	3%
Anabranches / Floodrunners (sub-bankfull	4.2	4.9	16%	4.4	4%
Floodplain (> bankfull)	1.4	1.2	-11%	1.3	-5%
Anabranches / Floodrunners (> bankfull)	1.4	1.2	-11%	1.3	-5%
Wetlands, billabongs, distributary channel	2.8	3.2	13%	2.7	-5%
Average	**3.6**	**3.9**	**10%**	**3.7**	**2%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes. There is limited sub-reach specific data on channel form and processes. Therefore, inferences have been made based on site-specific data (e.g., from the CEWO MER project) and what is known about the broader Edward/Kolety-Wakool system of which this sub-reach is a part.

7. References

Green, Damian. (2000). *The Edward/Wakool system: River regulation and environmental flows*. Report prepared for the Department of Land and Water Conservation, Murray Region, Deniliquin.

Tulau, M & Morand, D. (2013). *Aspects of Quaternary geology, geomorphic history, stratigraphy, soils and hydrogeology in the Edward-Wakool channel system with particular reference to the distribution of sulfidic channel sediments.* Report prepared by Office of Environment and Heritage for Southern Cross geoscience, Southern Cross University and the Murray Darling Basin Authority.

Watts R.J., Bond N.R, Healy S., Liu X., McCasker N.G., Siebers A., Sutton N., Thiem J.D., Trethewie J.A., Vietz G., Wright D.W. (2020). *Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project: Edward/Kolety-Wakool River System Selected Area Technical Report, 2019-20*. Report prepared for Commonwealth Environmental Water Office.

Sub-Reach 15 – Mid Niemur Reach

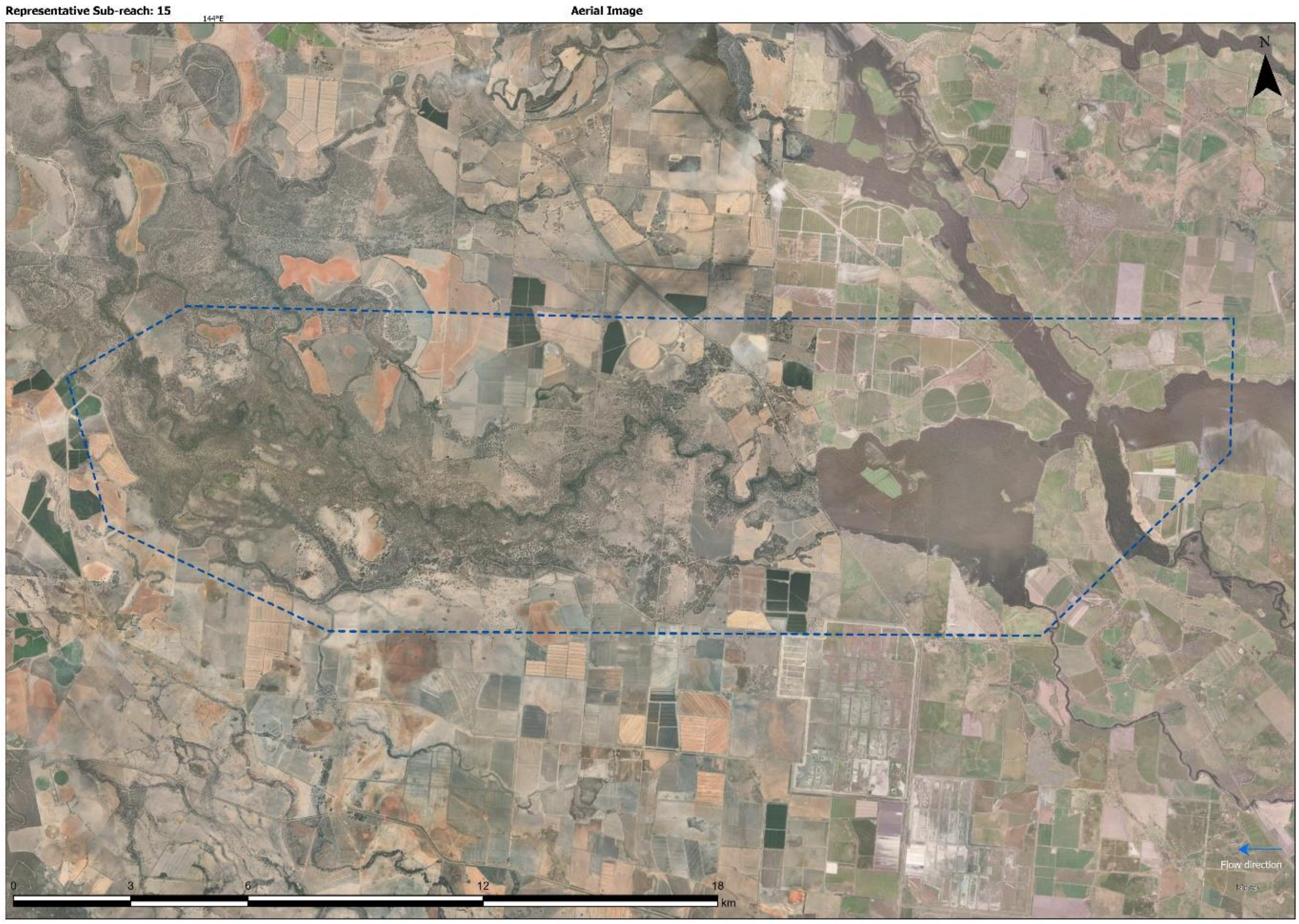

Figure 1 Sub-reach map extent

1. Subreach position in catchment and general description

The sub-reach is on the Niemur River is around 4 km downstream of where the creek intersects with Murrain Yarrein and Cockran Creek. Jimaringle Creek, a distributary channel of Cockran Creek, joins the Neimur River at the upstream of the sub-reach extent. Cockram Creek is a branch of Colligen Creek (itself an anabranch of the Edward River). Both Murrain Yarrein and Cockran Creek are confined within an ancestral channel while the Neimur River downstream takes a more distributary form (Green, 2000).

Downstream of Steven's weir, flows from the Edward River to the Neimur River are highly controlled, through regulators on Tumudgery, Junction and Red Bed Creeks in the Werai Forest section, although flood flows also pass down these waterways. The river can also receive regulated flows from Colligen Creek upstream of Steven's Weir. Neither Cockran Creek or Jimaringle Creek receive regulated flows and only flow intermittently.

The majority of the channel has been classed as Meandering Fine Grained by the RiverStyles assessments. These assessments also suggest the river is in moderate condition and has low fragility with a moderate recovery potential.

2. Channel form and processes

a. Anthropogenic changes

Steven's Weir, built in 1935, controls flow in the Edward River downstream of Deniliquin for irrigation. Upstream of the weir, a regulator controls flows into Colligen Creek which then flow into the Neimur River; while of the weir regulators in the Werai Forest on Tumudgery, Junction and Red Bed Creeks can also divert flows to the river.

Within the sub-reach there are numerous irrigation channels and levees.

b. Historic changes based on the historical imagery

The planform of the river has not changed since 1945, with little observable lateral migration or channel change.

There has been a limited increase in riparian and floodplain vegetation since 1945 particularly as the river flows downstream but no observable increase in instream large wood or visible features in the channel.

c. Forms (mainly based on LiDAR)

As the Neimur River crossing the ancestral channel form of Murrain Yarrein and Cockran Creek the channel appears more confined that upstream and downstream sections. Between Cockran Creek and Moulamein Road several meander cutoffs are visible. Downstream of Moulamein Road the planform becomes more distributary in nature, with indistinct floodout and effluent creek channels forming on the floodplain.

Within the sub-reach the Neimur River channel meanders through a low elevation forested area. The channel is around 20 m wide with steep banks around 2-3 m high, that appear generally stable (Site 35 and 43 from Tulau and Morand, 2013). Downstream the channel narrows to around 5-7 m in width as flows are distributed onto the floodplain through floodouts or breakaways. The banks remain steep but generally stable (Site 29 from Tulau and Morand, 2013)

Bank erosion appears to be dominated by fluvial entrainment based on the smooth and steep shape of the riverbanks.

In-stream the channel appears to comprise a mostly clay bed and banks with abundant logs and woody debris present (Tulau and Morand, 2013). However, Green (2000) commented on exposure of shallow sandy beaches on the Niemur River under low regulated flow conditions.

Current bedload accumulation is predicted to be low along with low suspended sediment load, although suspended load rates are estimated to be 2-10 times higher than natural conditions (Moran et al, 2005).

d. Processes

There is little evidence of change along the sub-reach. The main form of riverbank erosion is assumed to be fluvial entrainment however the process is slow and limited lateral migration can be seen.

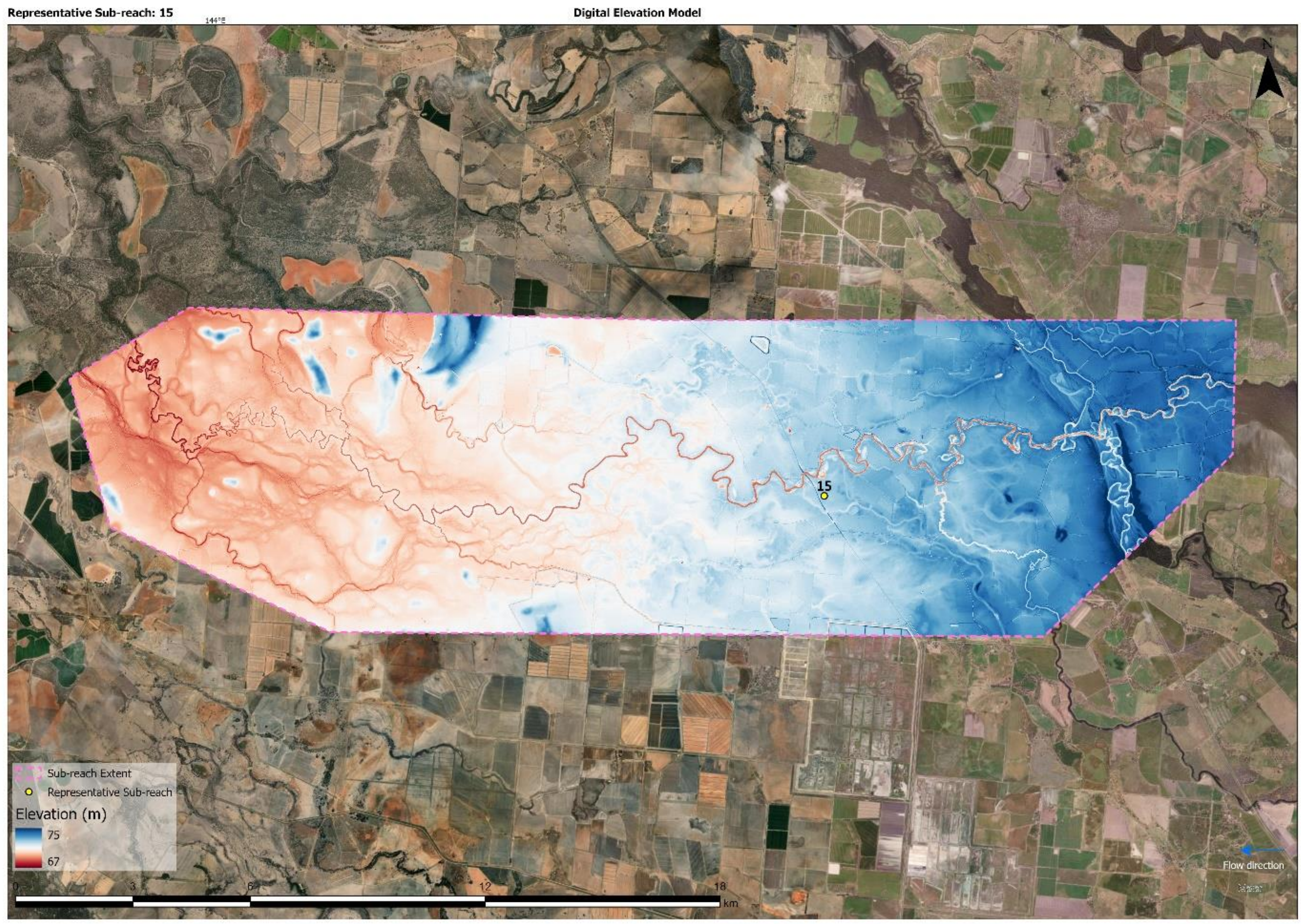

Figure 2 Lidar imagery of the sub-reach showing the different geomorphic features present

3. Floodplain form and process

a. Anthropogenic changes

Construction of irrigation channels and levees across the floodplain has substantially altered floodplain inundation patterns. There are also numerous irrigation "escapes" and surface drains as well as levees (Green, 2000).

b. Historic changes based on the historical imagery

There has been an increase in floodplain vegetation from 1945, mainly along the channel margins. Across the floodplain, land development for irrigated farming has significantly increased with levees built to the north and south at the floodplain margins. Areas of floodplain have been recontoured and channels and drains constructed.

c. Hydrological connections

The floodplain extent is constrained to the north and south by levees which limit flows across agricultural land. Flows can move out across the floodplain via the floodouts and creek channels (including Buccaneit Creek, Pelham Creek, Burragorrima Creek, Ooronong Creek and Middle Creek; DECCW, 2011) which connect above 3000 ML/d. There is a low natural levee along sections of the banks of the main river channel similar to other distributary systems like the Barmah-Millewa reach of the River Murray.

Inundation mapping shows that downstream of Moulamein Road, flooding commences from around 4000 to 7000 ML/d. The floodplain width is 5-7km (DECCW, 2011). Upstream, the floodplain looks to be engaged for flows above 11,000 ML/d. The Moulamein Road provides a barrier to floodplain flows moving downstream.

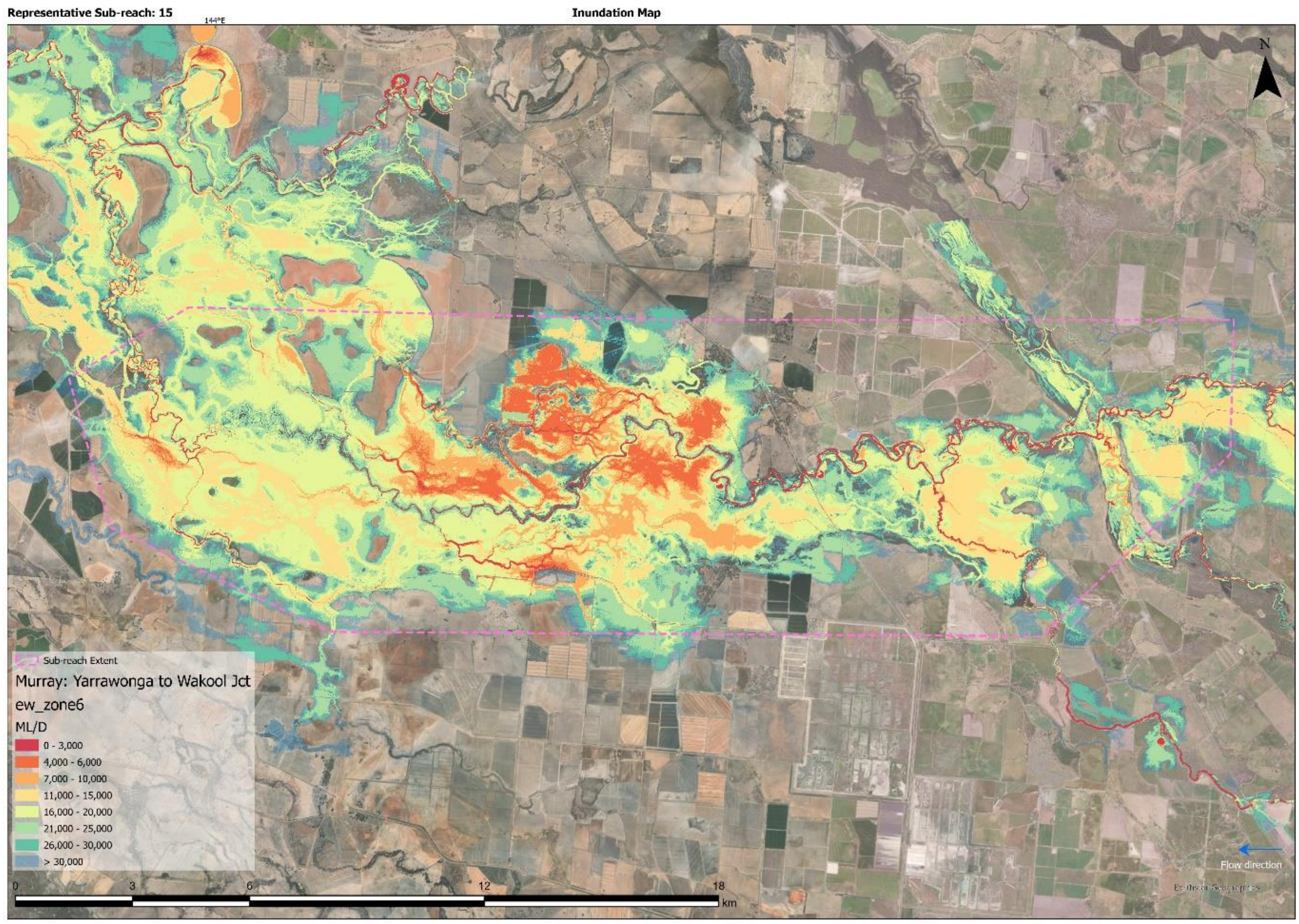

Figure 3 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

d. Form (mainly based on LiDAR)

Through the sub-reach, downstream of Moulamein Road the channel gradient becomes lower, with a pinnate drainage network across the floodplain. Floodouts and minor effluent creek channels are visible. A paleolake feature with a lunette is visible at the downstream of the sub-reach. Along the margins of the floodplain the features are truncated or modified via levees and agricultural development.

e. Processes

This low energy environment distributes water across the floodplain. The main processes affecting floodplain flows are the increasing levee and channel network which has expanded over time.

4. Base case

The base case geomorphic features and processes are summarised in *Table **1***

Table 1   Geomorphic Features and Processes

Geomorphic Feature	Process
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Infilling
Floodplain (> bankfull – anabranches/floodrunners)	Infilling
Floodplain (> bankfull connection)	Sediment deposition
Floodplain (wetlands / billabongs / distributary channels)	Sediment connectivity

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the ‘level of association’). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 15 are summarised in *Table* **3**. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This reach receives flows from the Edward River systems via the River Murray.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Flows from the Edward River are most likely to be influenced by the flow option scenarios and therefore these flows have been applied in the analysis based on the results for Niemur River at Moulamein Road.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Cutoffs	Meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Infilling	0	3	3	2	2
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Infilling	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**0.91**	**0.88**	**0.67**	**0.55**	**0.25**
Likelihood (Y45D40 events per year)		0.93	0.93	0.84	0.71	0.23
Likelihood (Y30D30 events per year)		0.93	0.89	0.83	0.63	0.24

Flows in the Niemur River including the sub-reach are highly regulated through the operation of Steven's weir and a range of other flow regulating structures. Green (2000) noted that prior to river regulation the Niemur River would have flowed most of the year with low flows occurring in late summer and autumn. It now receives regulated flows over the summer and autumn months with river levels reduced only for a short period in June. The river also receives drainage and stormwater from the various irrigation networks.

The Niemur River channel is at its widest through this sub-reach but decreases in size and capacity in the downstream direction as effluent channels and floodouts distribute flows and energy onto the floodplain. There appears to be some suspended sediment transport but limited bedload.

Current conditions (base case) indicate a low energy environment with limited channel or floodplain change except where the floodplain is confined by artificial structures such as levees, channels and drains.

Under the flow options scenarios there is limited change in the flow regime for this sub-reach compared to current constraints across sub-bankfull flows. Increasing flows within the bankfull and above range may activate or trigger processes such as cutoffs and anabranch development. However, it is unlikely that for a low energy river such as this that the changes in flow regime will result in rapid changes to the geomorphic features and processes above current rates of change.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Cutoffs	7.1	8.1	14%	7.8	10%
Anabranches / Floodrunners (sub-bankfull)	6.2	7.2	15%	6.9	10%
Floodplain (> bankfull)	2.4	2.8	16%	2.6	8%
Anabranches / Floodrunners (> bankfull)	2.4	2.8	16%	2.6	8%
Wetlands, billabongs, distributary channels	4.4	5.3	20%	5.1	15%
Average	**4.5**	**5.2**	**16%**	**5.0**	**11%**

Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes. There is limited sub-reach specific data on channel form and processes. Therefore, inferences have been made based on what is known about the broader Edward/Kolety-Wakool system of which this sub-reach is a part.

References

Tulau, M & Morand, D. (2013). *Aspects of Quaternary geology, geomorphic history, stratigraphy, soils and hydrogeology in the Edward-Wakool channel system with particular reference to the distribution of sulfidic channel sediments.* Report prepared by Office of Environment and Heritage for Southern Cross geoscience, Southern Cross University and the Murray Darling Basin Authority

Department of Environment Climate Change and Water NSW (2011). Floodplain Management Plan Edward and Niemur Rivers Stage 3, Department of Environment Climate Change and Water NSW

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Moran, C. Prosser, I. DeRose, R. Lu, H. Croke, B. Hughes, A. Olley, J. and Cannon, G. (2005) Sediment and nutrients in rivers of the Murray-Darling Basin: Targeting the future, Murray-Darling Basin Commission Knowledge Series 14/05, MDBC, Canberra

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Sub-Reach 16 Geomorphic Outline – Gunbower Wakool / Lower Wakool Reaches

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

This sub-reach of the Murray River is located at the confluence of the Edward and Wakool River systems. It is located towards the boundary of the Lower Alluvial Fan zone and the Bungunnia Zone.

There are no townships or significant roads in this area.

Within the sub-reach extent, a roughly triangular area of “black country” is set into a broad area of red Woorinen dunefield which sits higher in the landscape. The black country is the combined floodplains of Edward and Wakool Rivers.

This reach is a major convergence point in the Murray River drainage network where the floodplain is 60 km wide (measurement at approx. site 15) comprising multiply intersecting shallow surface drainage collapsing into a flow path ~4 km wide. This reach potentially receives flow from several sources.

The present-day river network is the Edwards and Wakool rivers: sinuous and actively migrating channels and their immediately adjacent modern floodplains. The Edwards River floodplain experiences inundation at lower flow levels than the Wakool River. The present-day rivers are set into a slightly higher alluvial terrace relating to ancestral rivers. This older alluvial terrace is also prone to inundation, but more rarely.

2. Channel form and processes

a. Anthropogenic changes

No anthropogenic changes were observed.

b. Historic changes based on the historical imagery

No historic changes were observed.

c. Landforms

The Edward River is a tightly but irregularly sinuous channel, occupying a narrow channel belt that also contains abundant cut of meander loops and scroll plains. The dimensions of its channel belt c.f. the infilled traces of larger ancestral channels nearby, and the elevation difference between scroll plains and flanking “black country” floodplain, indicate that the present-day river is semi-confined within the footprint of an ancestral channel and ancestral alluvial terraces.

The Wakool River is mostly low-sinuosity, occupying a narrow channel belt that is contained within alluvial terraces and has dimensions consistent with being partially-infilled ancestral channel.

Bucky Creek is an anabranch channel fed by a bank-breach offtake on an outer bend of the Wakool River and rejoining the Wakool downstream from the Wakool-Edwards confluence. It is sinuous and contained within the footprint of an ancestral channel. The central reaches are confined by alluvial terraces but the upstream and downstream reaches are functionally unconfined within the ancestral channel.

The Wakool-Edwards confluence is also within the footprint of partially infilled ancestral channels.

There appear to be currently active point bars just near the Edwards/Wakool confluence.

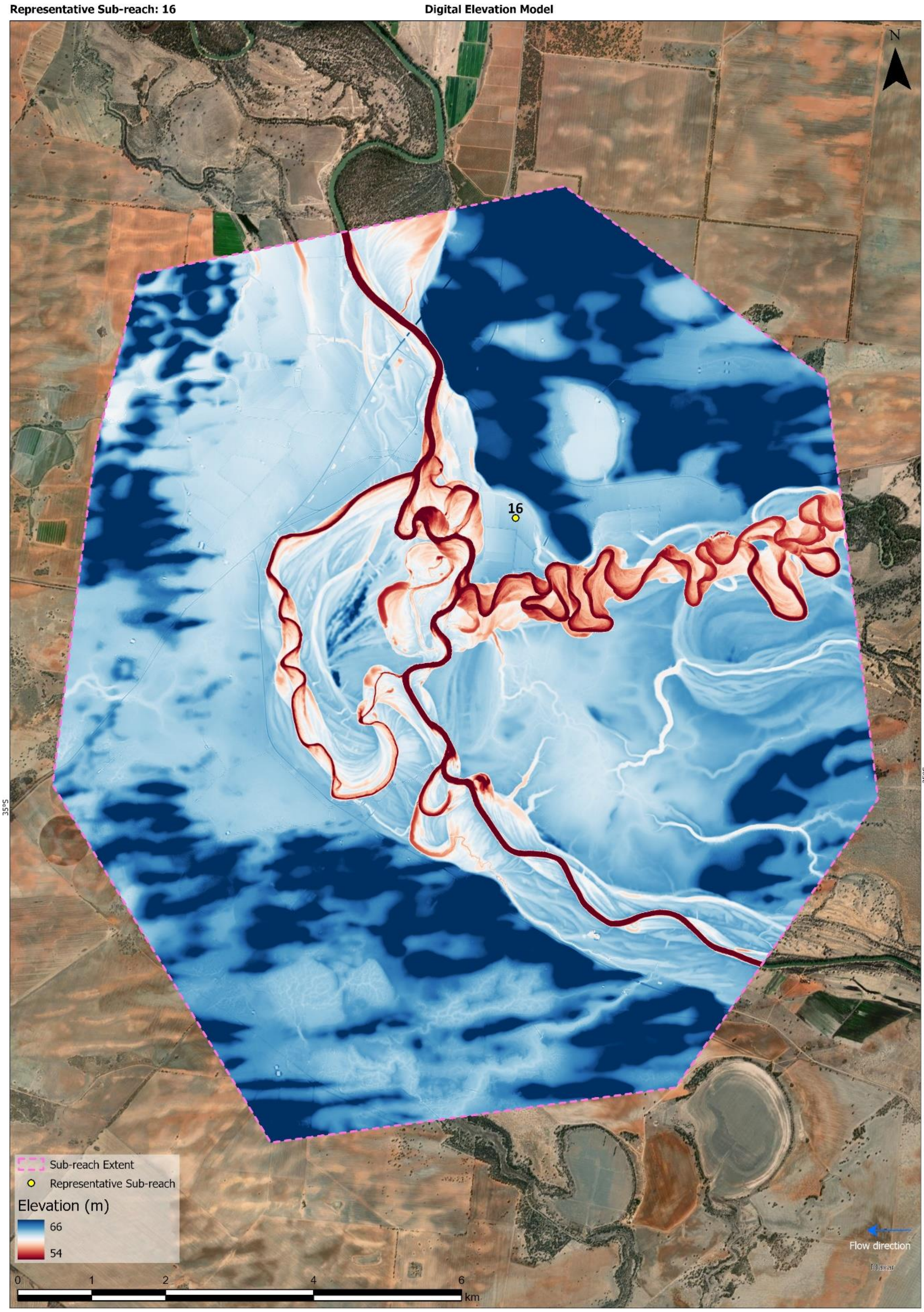

Figure 2 Lidar imagery of the sub-reach showing the different geomorphic features present

d. Processes

The abundant scroll plains and meander cut-offs indicates the Edward River has experienced significant lateral migration over time. Channel migration is incremental and can be either towards increasing sinuosity or towards downvalley translocation, depending on local context.

The scroll plains of the Wakool River and Bucky Creek channels are less densely vegetated, and the successive banks are less tightly packed together. This suggests lower discharge: less frequent or less powerful flows, resulting in less vegetation and lower levels of geomorphic activity.

The channel of the Wakool River migrates incrementally downvalley.

Bucky Creek's scroll plain orientation indicates that in the central section of this creek the channel migrates by downvalley translation of meander bends, but in the upstream and downstream reaches the channel develops increasing sinuosity. It appears dry in most aerial imagery.

These rivers will behave as semi-confined channels at bankfull flow or low floods but may behave as unconfined rivers if a large flood inundate the entire floodplain (including the ancestral floodplain).

3. Floodplain form and process

e. Anthropogenic changes

There are several irrigation channels and offtakes along the southern boundary of the Wakool River in this reach.

a. Historic changes based on the historical imagery

Aside from the development of some cropping land in the more elevated and valley-marginal floodplain, no historic changes were observed.

b. Hydrological connections

In the Edwards River inundation of the modern floodplain takes place at >7000 ML/d. In the Wakool River upstream from the confluence, very little of the floodplain will be inundated even at levels >31,000 ML/D. Downstream from the confluence, floodplain inundation along the Wakool River commences at around 11,000 ML/d.

This contrasts with the banks of the ancestral rivers, which have connections extending onto the higher alluvial terrace. These breaches are active in the present day (evidence: lined by riparian vegetation and associated with vegetation at their distal termini). They contribute to inundation of the ancestral floodplain at flows of >26,000 ML/d. To the south of the defined reach extent, Genoe Creek is one such connection (-35.03°, 143.51°), which can deliver water to several lakes, water storages and floodplain wetlands.

Representative Sub-reach: 16 **Inundation Map**

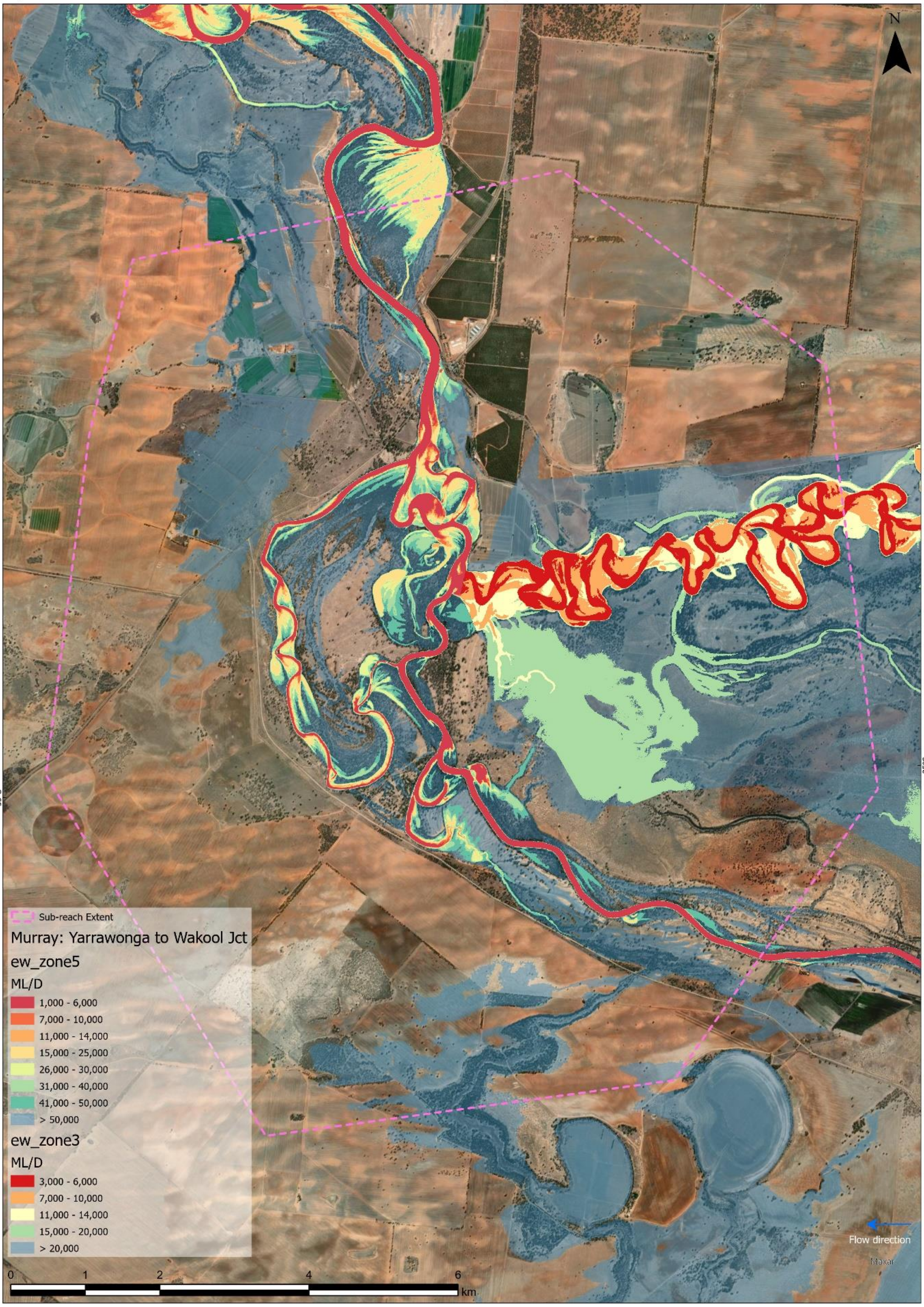

Figure 3 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

c. Landforms

The “black country” is mostly floodplain from the ancestral rivers: it is slightly higher in elevation than the floodplain immediately adjacent to the modern channels. This higher area carries few flood runners, mostly distributary channels from old bank breaches in the ancestral channels. There is also a single patch of high-elevation “red country”, which is bisected by a Channel Country-type waterhole.

There are at least three ancestral channels visible. Although mostly infilled, they continue to exercise influence over the present-day rivers. These are the ancestral-Edwards, the ancestral-Wakool, and another at -34.99° 143.53° (in the present-day inset carries a string of discontinuous channel segments). At the Edwards/Wakool confluence, a loop of the ancestral river was isolated by chute cut-off: the loop now contains Bucky Creek, and the chute cut-off now contains the Wakool River and the confluence location.

The floodplains of the present-day rivers are immediately adjacent to the channels, and at a slightly lower elevation than the ancestral floodplain.

The Edward River floodplain is partially discontinuous, with the channel confined within slightly higher alluvial terraces of the ancestral rivers. The floodplain has abundant scroll plains and sinuous channel segments isolated by meander neck cut-off. The geometry of the scroll plains varies between parallel with the downvalley meander limb (where the meanders are confined) and concentric with the meander outer bend (where meander apices have space to expand into).

Wakool River scroll plain orientation is mostly parallel with the downvalley meander limb.
indicates downvalley translation of meander bends.

d. Processes

In the present-day rivers, preservation of the scroll plain and incomplete infill of the abandoned channels suggest that vertical aggradation in the floodplain is not a major component of sediment deposition.

The Channel Country-type waterhole on the higher alluvial terrace and the channel segments in the third partially infilled ancestral channel indicate that floodplain-level flow has taken place in the relatively recent past. Such flow has been sufficient to develop channel segments where locally high-energy conditions were encouraged by flow concentration, but insufficient to impact any other areas within the sub-reach.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel / Floodplain (sub-bankfull connections)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition
Floodplain (wetlands)	Sediment connectivity

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the ‘level of association’). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 15 are summarised Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This sub-reach receives flows from the Edward River and Wakool River.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an “impact score” for the main geomorphic features and processes relevant to this sub-reach.

Flows can be influenced by both river systems. We have completed the analysis based on the results for the Wakool River at Stoney Crossing. Similar results occur if the analysis uses Edward River flows.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Cutoffs	Meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Erosion	0	3	3	3	2
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Erosion	0	0	0	3	3
Wetlands, billabongs, distributary channels	Sediment Deposition	0	0	3	3	3
Likelihood (current constraints events/yr)		**0.67**	**0.52**	**0.46**	**0.37**	**0.36**
Likelihood (Y45D40 events per year)		0.83	0.67	0.57	0.41	0.37
Likelihood (Y30D30 events per year)		0.82	0.56	0.48	0.38	0.36

The Edwards and Wakool rivers merge in this area. Both are creeks with sinuous and actively meandering channels, and adjacent floodplains with ridge-and-swale topography. The Edwards River appears to carry more flow, and its floodplain is inundated at lower flows. The locations and behaviours of the present-day rivers are strongly influenced by the presence of a higher older alluvial terrace and its associated ancestral channels (now mostly infilled).

In-channel bars and benches appear stable with little change in planform visible between historic imagery (1960's) and present. Although some bars such, as at the confluence of the two rivers, are more heavily vegetated indicting increasing stability likely due to reduced flood flows in these rivers.

Current conditions (base case) indicate a low energy environment with limited channel or floodplain change.

Under the flow options scenarios there is some change in the flow regime for this sub-bankfull and bankfull flows in this sub-reach compared to current constraints. It is unlikely that for a low energy river such as this that the changes in flow regime will result in noticeable changes to the geomorphic features and processes above current rates of change

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Cutoffs	5.3	6.2	18%	5.6	6%
Anabranches / Floodrunners (sub-bankfull)	4.8	5.7	20%	5.0	5%
Floodplain (> bankfull)	2.2	2.3	8%	2.2	2%
Anabranches / Floodrunners (> bankfull)	2.2	2.3	8%	2.2	2%
Wetlands, billabongs, distributary channels	3.6	4.0	14%	3.7	3%
Average	**3.6**	**4.1**	**15%**	**3.7**	**4%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes. There is limited sub-reach specific data on channel form and processes. Therefore, inferences have been made based on site-specific data (e.g., from the CEWO MER project) and what is known about the broader Edward/Kolety-Wakool system of which this sub-reach is a part.

7. References

Tulau, M & Morand, D. (2013). *Aspects of Quaternary geology, geomorphic history, stratigraphy, soils and hydrogeology in the Edward-Wakool channel system with particular reference to the distribution of sulfidic channel sediments.* Report prepared by Office of Environment and Heritage for Southern Cross geoscience, Southern Cross University and the Murray Darling Basin Authority

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Watts R.J., Bond N.R, Healy S., Liu X., McCasker N.G., Siebers A., Sutton N., Thiem J.D., Trethewie J.A., Vietz G., Wright D.W. (2020). *Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project: Edward/Kolety-Wakool River System Selected Area Technical Report, 2019-20*. Report prepared for Commonwealth Environmental Water Office

Sub-Reach 17 Geomorphic Outline – Wakool Reach

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

This sub-reach is located at the confluence of the Murray and Murrumbidgee Rivers, near Boundary Bend. It lies within the Bungunnia landscape zone. There are few towns nearby and most of the agricultural landuse is cropping.

The sub-reach extent is a broad area of "black country", into which the rivers enter from the west and south-west, set into higher elevation "red country" which is mostly Woorinen sandplain. The "black country" contains

- slightly lower-elevation areas related to the modern rivers' channels and floodplains,
- slightly higher elevation country, relatively poorly vegetated, that is probably the ancestral floodplain,
- and broad swales that are the mostly infilled ancestral channels.

Some of the ancestral channel swales are heavily masked by the overprint of the present-day Murray and Murrumbidgee Rivers. Some are still clearly visible on satellite image and lidar and are characterised by swale like topography and less abundant vegetation; most of these carry small creeks (Manie Creek, Jack O'Brien's Creek, Peacock Creek) or discontinuous channel segments along the flow path.

The Murrumbidgee River is small, sinuous, and actively meandering. The Murray River is large, sinuous, and actively meandering. The alluvial surfaces have an irregular topography because of the combined influences of ancestral and modern rivers. Inundation patterns broadly follow present-day floodplains and the swales of infilled ancestral channels.

2. Channel form and processes

a. Anthropogenic changes

The floodplain areas have been impacted by agricultural development including increasing extent of irrigation horticultural development.

b. Historic changes based on the historical imagery

In the 1953 aerial photography, Jack O'Brien's Creek does not appear to have an active outlet, although most of its course is visible. In the present-day, the satellite image and lidar both show an active outlet.

Infrastructure for cropping is much more intensive presently than it was in 1953, and the deep green of the crop fields indicates substantial irrigation.

Representative Sub-reach: 17 **Historical Image**

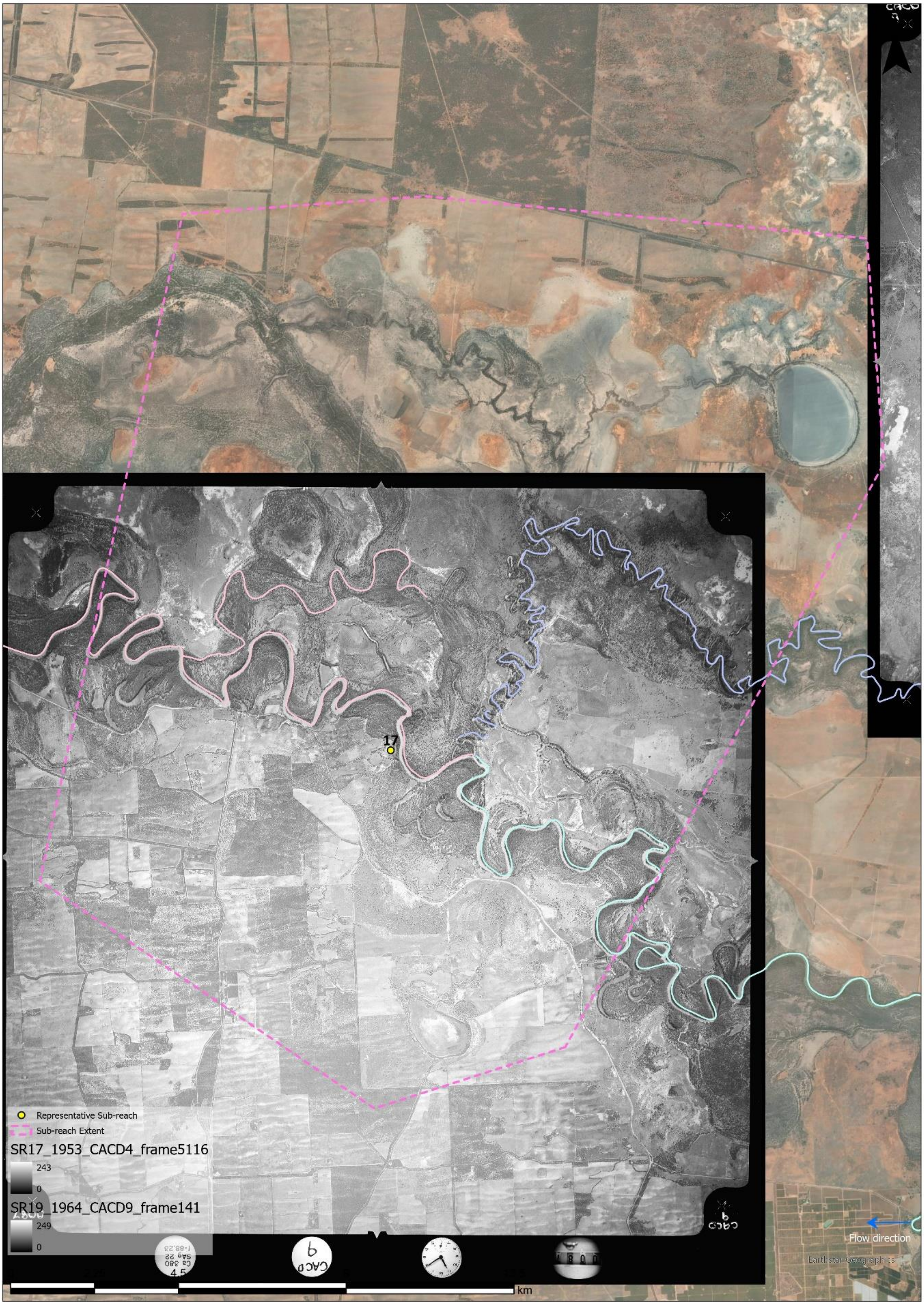

Figure 2 Historic imagery (circa 1953) of the sub-reach extent

c. Landforms

Murrumbidgee River: tightly and irregularly sinuous single channel following a broadly looping flow path that probably reflects the ancestral river. The floodplain immediately adjacent to the channel is densely vegetated and has scroll plains and areas of meander cut-offs. The lidar indicates levees along some channels, and there are some breaks in the levee with short offtake channels. The channel at the confluence is around 35m wide, compared to the adjacent Murray River channel width of 95 m.

Murray River: an irregularly sinuous single channel, with adjacent floodplains showing abundant scroll plains and meander cut-offs. The present-day river occupies and overprints ancestral channel in places, but the modern channel does not appear to be confined by the ancestral channel's margins.

The Murray-Murrumbidgee confluence appears to be a simple intersection of channels, without signs of erosion or sediment deposition. This suggests the Murrumbidgee River's input is low-energy and low in sediment load. Downstream of the confluence, several sandy point bars are present within the River Murray channel and appear relatively stable, with little change in extent in available imagery (Google imagery except for increasing vegetation encroachment.

Where water flows out into the broad swales formed by ancestral channels these form small, highly sinuous meandering creeks, confined by the ancestral channel topography. Those fed by the Murray River have broad scroll plains and are actively meandering (e.g., Jack O'Brien's Creek), those receiving less water have minimal and poorly developed scroll plains (e.g., Manie Creek) or diffuse flow paths with small discontinuous channel segments (Peacock Creek). Jack O'Brien's Creek is fed by an offtake from the Murrumbidgee River, and most of its length shows well developed scroll plains. Its outlet into the Murray River appears to be younger than the rest of the creek.

d. Processes

Murrumbidgee River: actively meandering within the pathway of an infilled ancestral channel. In many places the DEM does not indicate that the present-day channel is confined within the ancestral channel, and there is a question why some of the Murrumbidgee doesn't occupy the lower-elevation pathway 2 km to the west (-34.70° 143.27°).

Murray River: the channel is incrementally migrating, probably relatively rapidly, and developing floodplain by point bar accretion and meander loop cut-offs. The modern river's scale and stream power appears to be sufficient to cut back into the ancestral channel's margins.

The smaller creeks are fed by offtake from the main channels, presumably during near-bankfull or over-bankfull levels.

Representative Sub-reach: 17 **Digital Elevation Model**

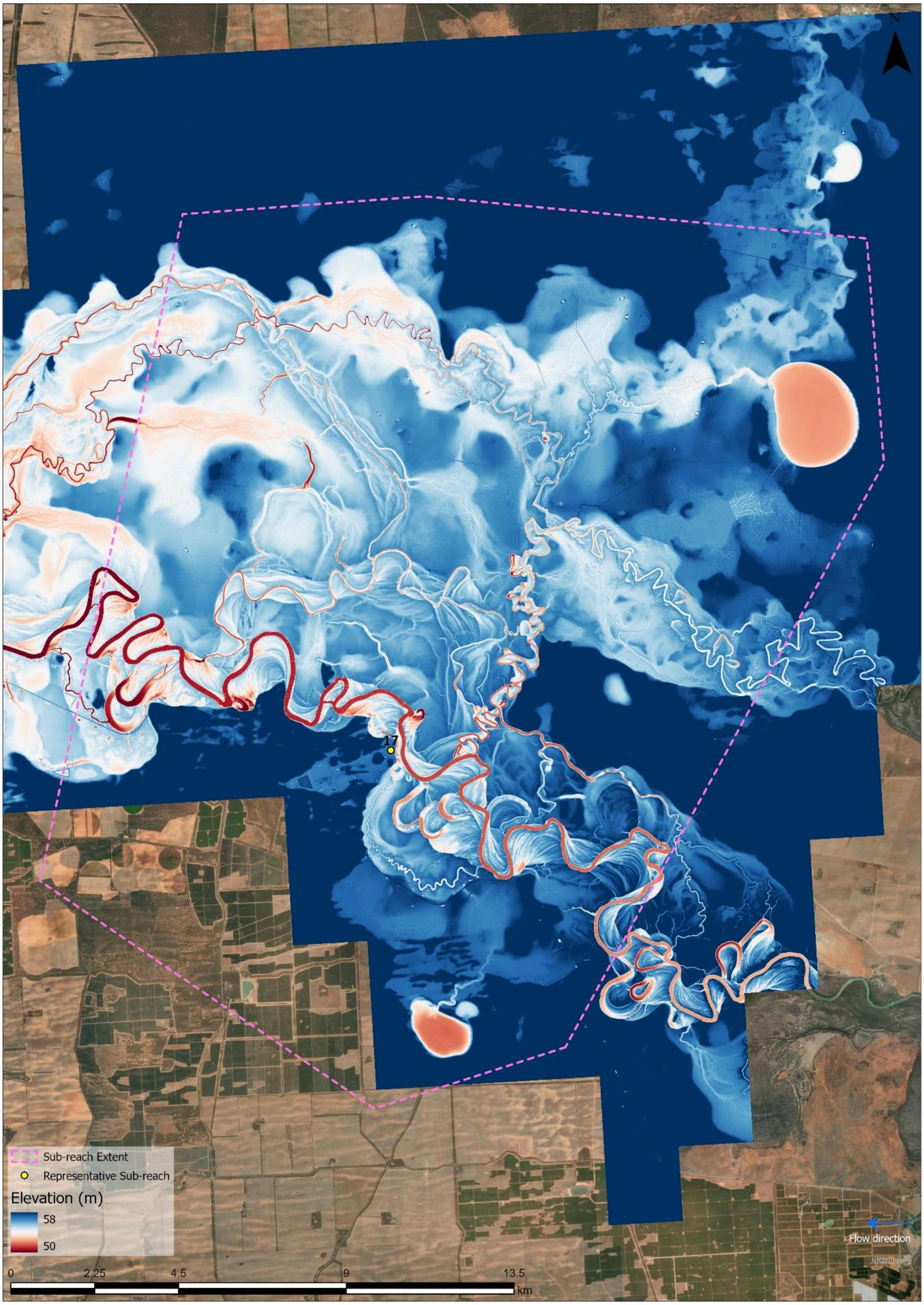

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

3. Floodplain form and process

e. Anthropogenic changes

Increasing agricultural development of the higher-elevation ancestral floodplain.

f. Hydrological connections

Breakaways and offtake channels deliver water onto the floodplain, where it is most likely to activate the small creeks and inundate near-channel scroll plains and the swales of ancestral channels.

Inundation mapping indicates the River Murray channel capacity is around 15,000 ML/d – 25,000 ML/d through this sub-reach, while the Murrumbidgee River channel capacity is only around 5,000 ML/d. Floodplain engagement along the River Murray is limited to floodplain features such as scroll bars and cutoff channels for flows up to 50,000 ML/d. The Murrumbidgee floodplain is engaged at much lower flows due to the lower main channel capacity.

The broader floodplain for flows > 50,000 ML/d is around 10 km wide (Currey and Dole, 1977) and has been described as a vast inland sea during flooding events, with lengthy inundation periods (Baker and Wright, 1977).

a. Landform

The modern floodplain immediately adjacent to the present-day river channels is densely vegetated and has scroll plains and areas of meander cut-offs.

The higher alluvial surface, probably floodplain of the ancestral channels, is of irregular but low-relief topography. In part this is due to the many swales of mostly infilled ancestral channels and the complex of small creeks, distributary flow paths, and discontinuous channels that now occupy the swales.

b. Processes

Overbank flooding likely drives geomorphic processes in this sub-reach, delivery water to small floodplain creeks and distal floodplain areas e.g., Middle and Manie Creeks.

Representative Sub-reach: 17 **Inundation Map**

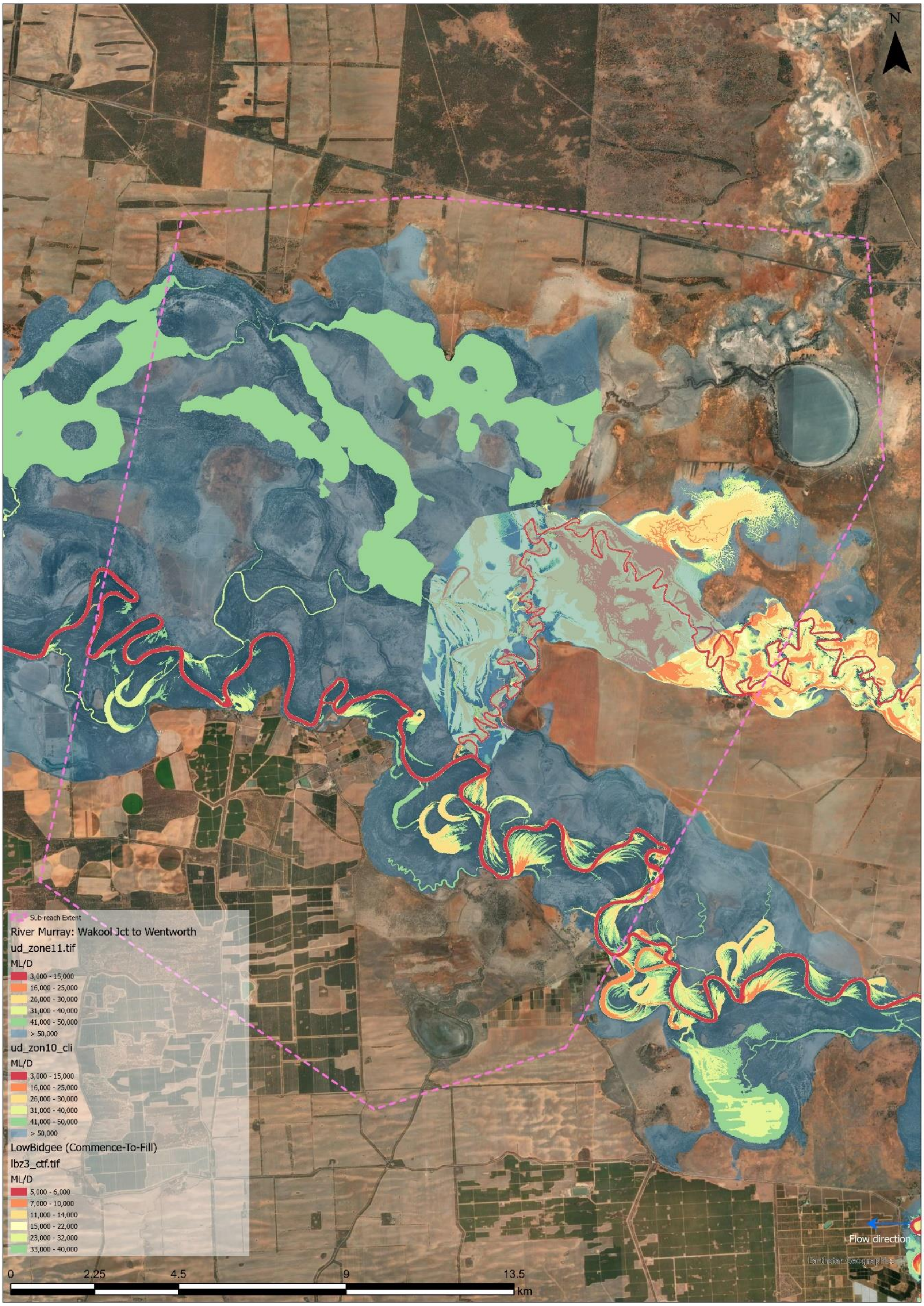

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel / Floodplain (sub-bankfull connections)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 17 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This sub-reach receives flows from the Murrumbidgee and Murray Rivers.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward RIver at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Flows can be influenced by both river systems. We have completed the analysis based on the results at Euston Weir.

Table 3 *Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios*

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Cutoffs	Meander migration	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Erosion	0	3	3	3	2
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Erosion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.88**	**0.43**	**0.31**	**0.23**
Likelihood (Y45D40 events per year)		1.00	0.89	0.41	0.31	0.20
Likelihood (Y30D30 events per year)		1.00	0.91	0.41	0.31	0.21

The modern Murray and Murrumbidgee River channels experience slow rates of lateral migration by active meandering processes. The modern floodplains are inundated by moderate flow events. Rates of geomorphic change are low due to the low gradient of the channels and floodplains with no large-scale change observed in the available information.

Current conditions (base case) indicate a low energy environment with limited channel or floodplain change.

Under the flow options scenarios there is actually a reduction minor reduction in the frequency of bankfull flows and limited change across the flow regime compared to current constraints. No geomorphic changes would be expected because of the proposed flow options scenarios.

Table 4 *Geomorphic impact score under current constraints and for the flow options scenarios*

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Cutoffs	5.7	5.5	-3%	5.6	-1%
Anabranches / Floodrunners (sub-bankfull)	5.3	5.2	-2%	5.3	0%
Floodplain (> bankfull)	1.6	1.5	-6%	1.6	-3%
Anabranches / Floodrunners (> bankfull)	1.6	1.5	-6%	1.6	-3%
Average	**3.5**	**3.4**	**-3%**	**3.5**	**-1%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Baker, B.W and Wright, G.L. (1977). The Murray Valley: its hydrologic regime and the effects of water development on the river. Proceedings of the Royal Society of Victoria, 90. 103-110

Currey, D.T and Dole, D.J. (1977). River Murray flood flow patterns and geomorphic tracts. Proceedings of the Royal Society of Victoria, 90, 67-77

Sub-Reach 18 Geomorphic Outline – Wakool Reach

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

This sub-reach is located adjacent to the Hattah-Kulkyne National Park in the Bungunnia landscape zone. It lies on the River Murray between Colignan (upstream) and Robinvale (downstream). Land use on the Victorian side is mostly National Park, but with well-developed cropping south of the park border. Land use on the NSW side of the river is a mixture of cleared paddocks and cropping.

In this reach the Murray River carries the integrated flow of the southern Murray Darling Basin drainage networks. Overall, this is a transport reach, with finer sediments in temporary floodplain storage and (presumably) bedload sediments in transport. There is little hydrological connection between the river and the wider landscape, except for distributary networks extending westwards.

The channel is single-thread, sinuous and meandering, flanked by "black country" floodplain that carries abundant imprints of active channel migration (scroll plains, oxbows, and neck cut-offs). The channel is partly confined between higher "red country", much of which is Woorinen duneplain. There is some mixed country, in which black floodplain and red sandplain are more closely intermingled, and these correspond to inundation areas (>50,000 ML/d). In some of this mixed country, the modern channel and its floodplain are slightly incised and confined by (presumably older) floodplain.

The modern drainage geometry is influenced by palaeolakes and the locations of ancestral channels. For example:

- the inundation area on the east of the sub-reach extent includes one or several lakes
- Lake Kramen on the south-west of the sub-reach extent is a palaeolake remnant
- Chalka Creek extends from an ancestral channel outer bank across a probable palaeolake to deliver water to the lakes of the Hattah-Kulkyne National Park on the Raak Plain.

2. Channel form and processes

a. Anthropogenic changes

Regulators now assist delivery of floodplain flows to the Hattah-Kulkyne National Park.

b. Historic changes based on the historical imagery

Most historical changes in this reach relate to the management of the Hattah-Kulkyne National Park.

c. Landforms

The channel is sinuous. Its degree of confinement varies locally between valley-controlled with discontinuous floodplain, to planform-controlled, becoming unconfined in the north of the defined reach extent. The scroll plains show meander development as increasing sinuosity where there is a lesser degree of valley confinement, and downvalley translation where the channel is more confined.

There is a relatively recent neck cut-off in the north (-34.67° 142.50°).

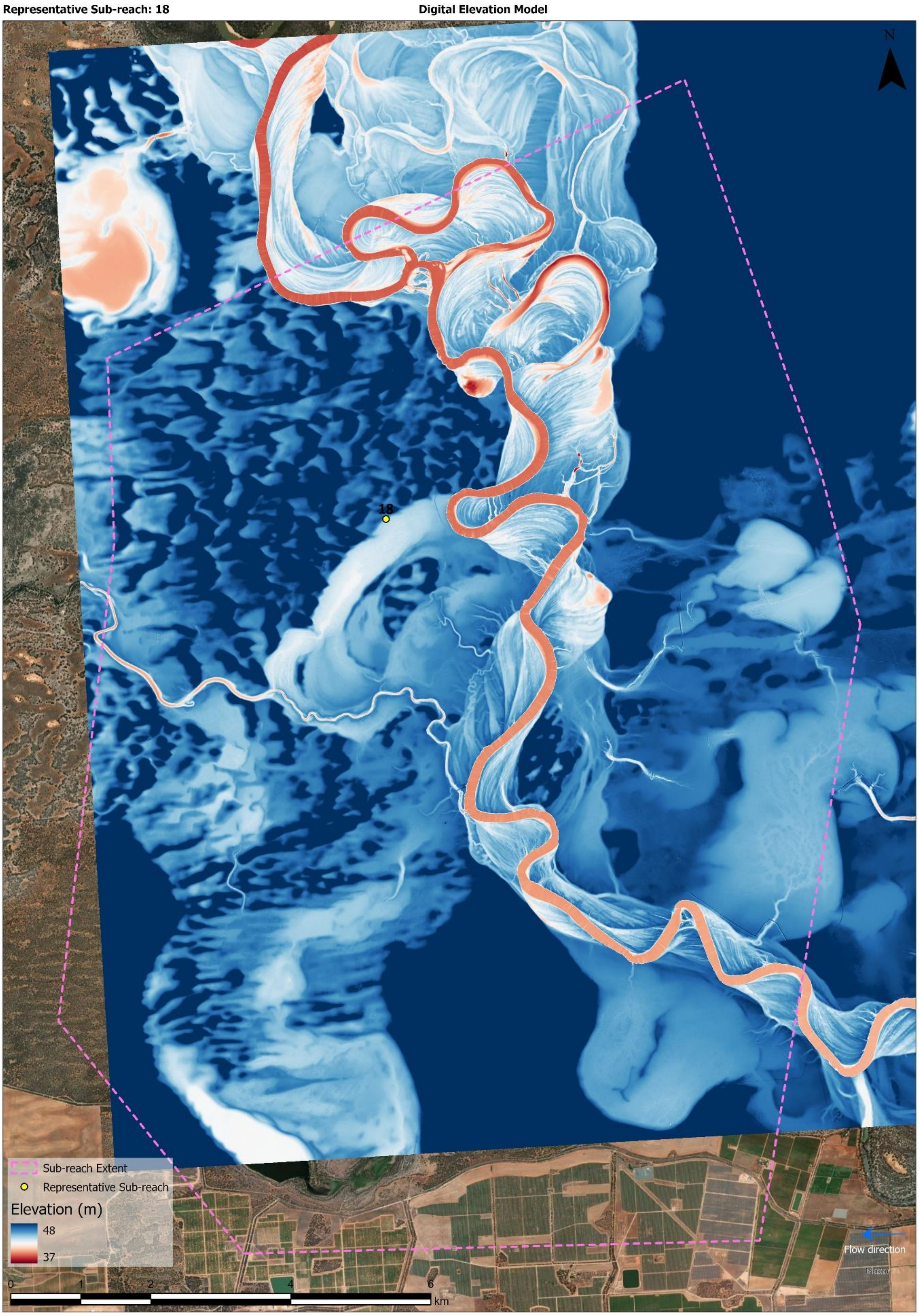

Figure 2 Lidar imagery of the sub-reach showing the different geomorphic features present

Many of the meander bends show (presumably sandy) point bars, most of which are also evident on the 1964 aerial photography.

There are several outer-bank overflow points on both modern and abandoned channels, leading to short effluent channels that drain onto the floodplain.

d. Processes

There is active incremental channel migration along this reach, increasing channel sinuosity where there is floodplain or abandoned channels to expand into, and shifting channel loops downvalley where the river is more confined however the rate of change is slow given the low gradient and energy of the system.

Sandy bars are present along bends along the reach which appear relatively stable as little erosion or accretion is noticeable in the available imagery from 2003 to 2020 (Google imagery).

3. Floodplain form and process

e. Anthropogenic changes

Some canal? works have been undertaken in the two small lakes to the east of the sub-reach extent (post-1964).

The road to the pumping station crosses Chalka Creek via a culvert that is narrower than the natural channel. The satellite imagery and lidar indicates that it is a slightly raised road.

f. Hydrological connections

At higher flows (>26,000 ML/d; >41,000 ML/d) water is delivered onto the floodplain through the effluent channels although inundation extents are limited in this flow range.

Chalka Creek has an outer-bank offtake from the main Murray channel, with a small slightly sinuous channel across the floodplain that links to a larger, probably ancestral Chalka Creek extending from an ancestral Murray channel outer bank across a probable palaeolake to deliver environmental water to the lakes of the Hattah-Kulkyne National Park on the Raak Plain. Although the present-day Chalka Creek obtains most of its waters from the channel, floodplain inundation >50,000 ML/d will also contribute water.

g. Landform

The floodplain is dominated by ridge-and-swale topography and the larger swales of abandoned channels. The floodplains support denser stands of larger and more water-requiring trees (stands of River Red Gum) in comparison to the sparser and xerophylic vegetation (mallee scrub) of the Woorinen Sands above the floodplain.

The flood basins that retain water (the lakes) have smoothed bottoms and gently curved shorelines.

h. Processes

Floodplain development occurs by lateral accretion during incremental channel migration; however the rates of change are low.

The lakes are experiencing lacustrine and nearshore geomorphic activity during lake-full conditions.

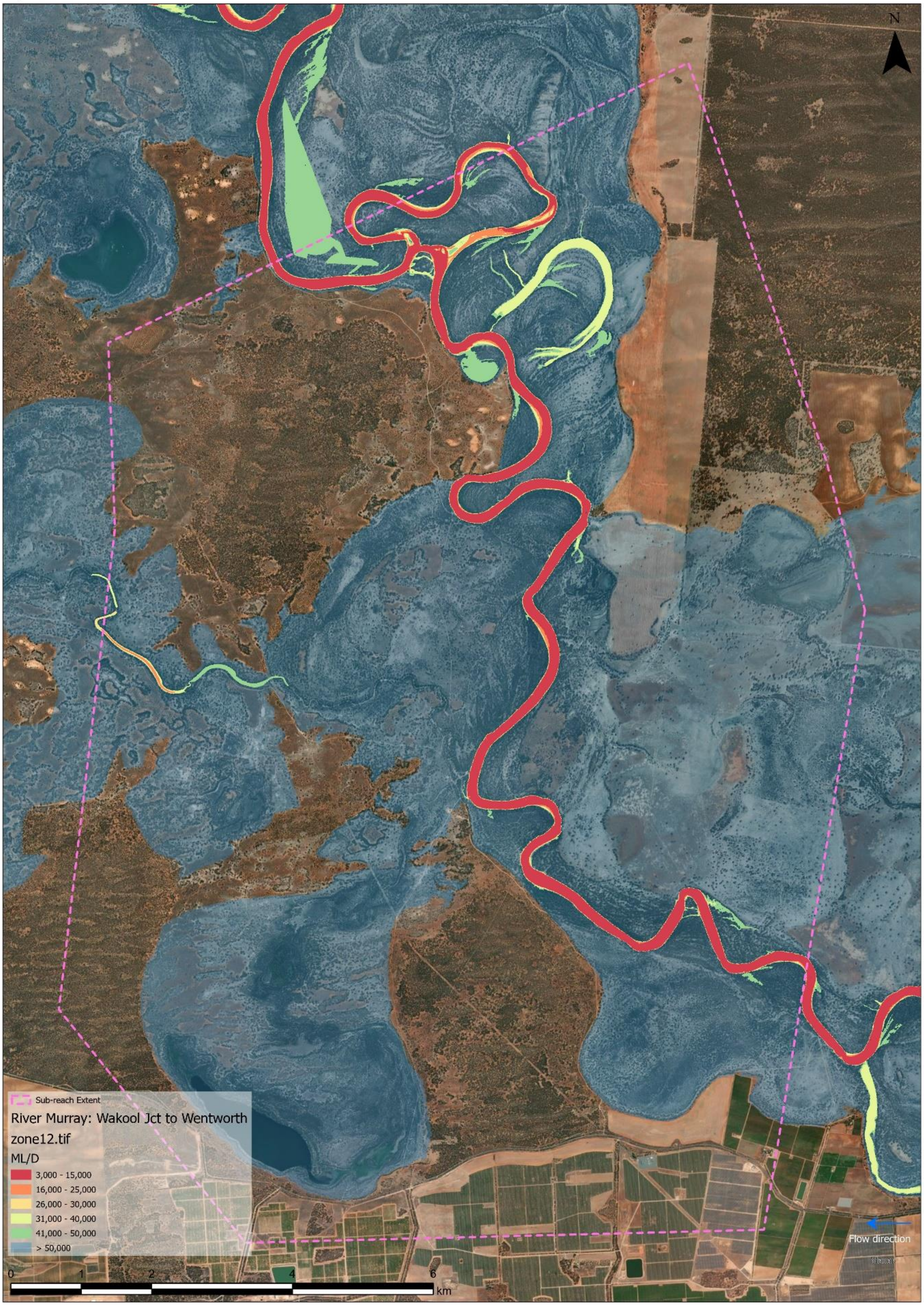

Figure 3 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Floodplain (cutoffs)	Meander migration
Floodplain (anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection))	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 18 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This sub-reach receives flows from the Murrumbidgee and Murray Rivers.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murray: Yarrawonga to Wakool junction	15,000 d/s of Yarrawonga Weir (current flow limit) 25,000 30,000 40,000 45,000	River Murray and floodplain from Yarrawonga Weir to Wakool junction including the Edward-Wakool River system and major effluents / anabranches e.g., Tuppal, Native Dog and Bullatale Creeks
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward RIver at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Flows can be influenced by both river systems. We have completed the analysis based on the results at Euston Weir as this provides the greater flow contribution.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Cutoffs	Meander migration	1	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.88**	**0.43**	**0.31**	**0.23**
Likelihood (Y45D40 events per year)		1.00	0.89	0.41	0.31	0.20
Likelihood (Y30D30 events per year)		1.00	0.91	0.41	0.31	0.21

The Murray River is partly confined within a valley of variable width, within which the channel is slowly actively meandering. Incremental channel migration takes place over long periods of time. Where the valley is particularly wide the channel becomes very sinuous and neck cut-offs occur. The ridge-and-swale floodplains are biologically productive, supported by inundation during flooding. In some places floodwaters are delivered to floodplains and distant wetlands by breakaways and effluent channels.

Current conditions (base case) indicate a low energy environment with limited channel or floodplain change.

Under the flow options scenarios change there is a little change in the flow frequency of the different flow categories. It is unlikely that for a low energy river such as this that such minor changes in flow regime will result in noticeable changes to the geomorphic features and processes above current rates of change.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	Y45D40	% change	Y30D30	% change
Cutoffs	5.7	5.5	-3%	5.6	-1%
Floodplain (> bankfull)	1.6	1.5	-6%	1.6	-3%
Anabranches / Floodrunners (> bankfull)	1.6	1.5	-6%	1.6	-3%
Average	**5.7**	**5.5**	**-3%**	**5.6**	**-1%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Gill, E.D. (1973). Geology and Geomorphology of the Murray River, Memoirs of Museum Victoria, Vol 34. P1-97

Currey, D.T. and Dole, D.J. (1978). River Murray Flow Patterns and Geomorphic Tracts, Proceedings of the Royal Society of Victoria, p67-77

Sub-Reach 19 Geomorphic Outline – Balranald Reach

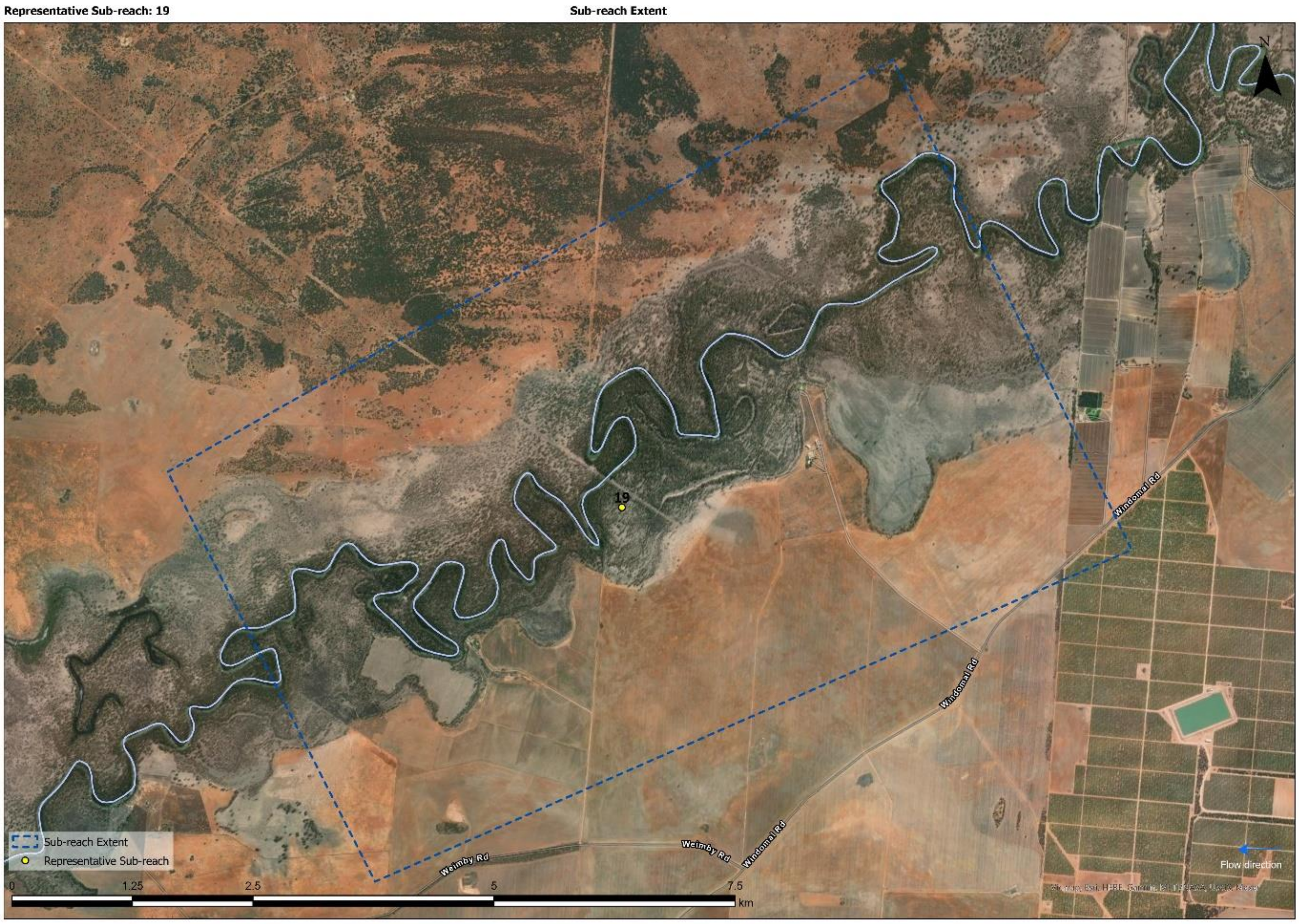

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

This sub-reach is located on the lower Murrumbidgee River downstream of Balranald. It lies at the boundary of the Lower Alluvial Plain and Bungunnia landscape zones. Land use varies between mostly uncleared paddocks, and limited cropping in the "black country" to more widespread cropping across some areas of "red country" to the southeast.

The Murrumbidgee River flows down a shallow valley of "black country". Higher elevation "red country" flanks the shallow valley and is largely above fluvial processes. The fluvial valley contains the present-day channel and its immediately adjacent floodplain, and wider floodplain that includes cut-off loops of the present-day channel, some scroll plains, and infilled traces of a larger ancestral channel. The present-day channel is in places semi-confined by the topography of the ancestral channel and is irregularly sinuous. Under non-regulated conditions it probably developed by incremental meandering during in-channel flow, and avulsive channel relocation during very large floods. Under regulated conditions, the channel appears to be stable.

This sub-reach lies downstream of the lower Murrumbidgee alluvial fan distributary system.

2. Channel form and processes

a. Anthropogenic changes

Approximately 1.7 km upvalley of the sub-reach extent, a cut was made across a channel bend, and the Balranald Weir was installed. The width of the constructed channel is approximately double that of the natural channel. The weir pool is used for stock and domestic water supply.

b. Historic changes based on the historical imagery

Within the sub-reach extent, there have been no significant channel changes visible on the imagery. Upstream, the Balranald Weir was installed after the 1964 aerial photography.

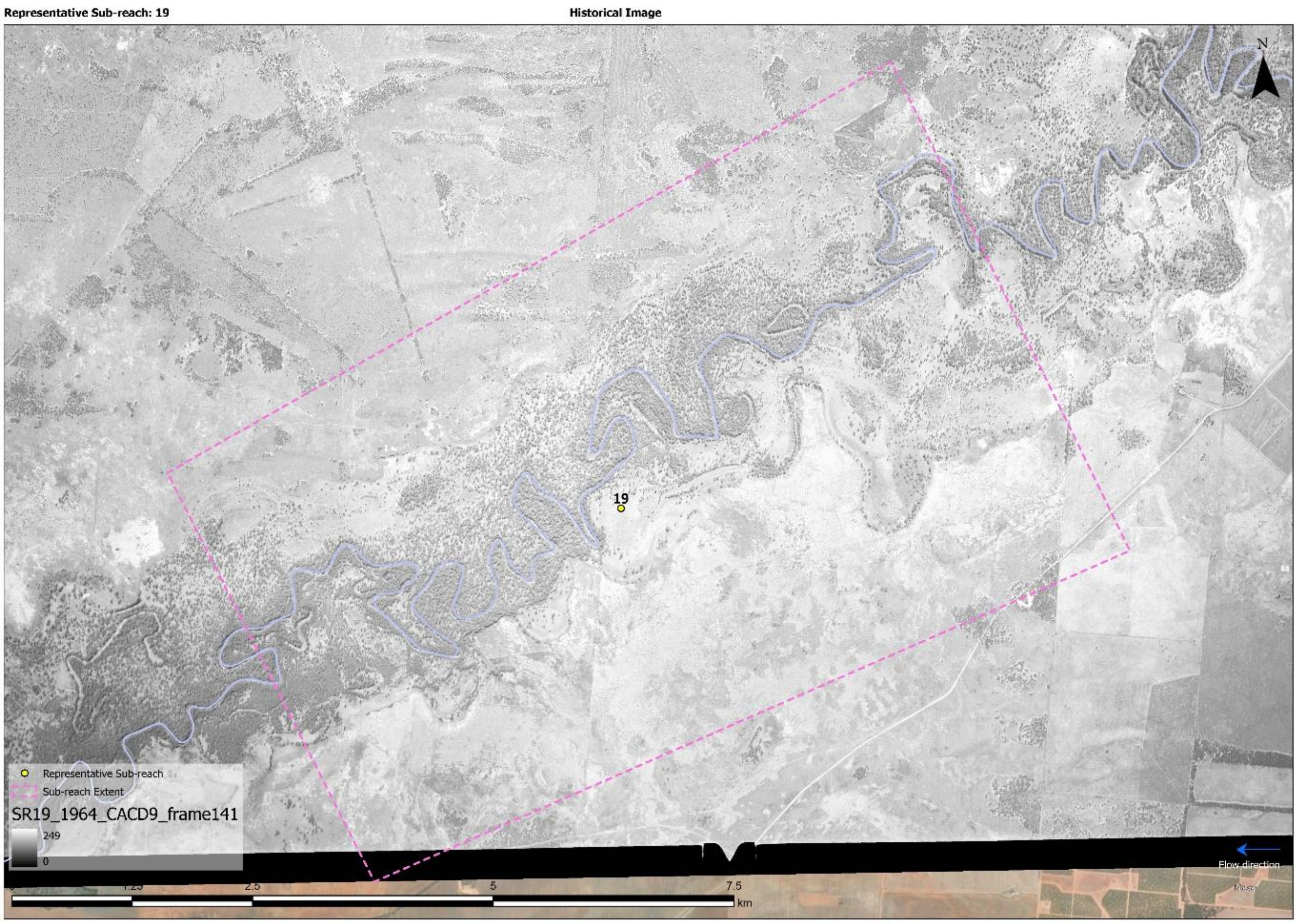

Figure 2 Historic imagery (circa 1964) of the sub-reach extent

c. Landforms

The Murrumbidgee River is underfit within a shallow valley that is the channel belt of the ancestral river system. Traces of the ancestral river's larger meander scale can be seen in the curves of the boundary between red and black country. The single-thread channel is sinuous and irregular. In places, the channel is associated with narrow scroll plains, but they are not very strongly expressed.

The channel is apparently unconfined within the valley, but its irregular sinuosity and vegetation distribution suggests that in places at least, the modern channel and immediately adjacent floodplain is slightly inset within an older fluvial terrace. For example, in the west (-34.70° 143.40°) the sinuous channel and its discontinuous floodplain is confined within the remnants of a larger ancestral channel; the apex of the outer-bank bends is cutting back into the (presumed) terrace.

Channel banks are heavily vegetated: there are no indications of point bar deposition or outer-bank retreat. In places, there are effluent channels or areas of lower bank that drain onto lower-elevation parts of the floodplain.

d. Processes

The channel has been actively meandering in the relatively recent past but does is not currently active. In its unregulated state, the channel would have shifted its position by a combination of incremental meander migration (probably during lower flow levels, in-channel flow) and higher-flow flood-driven channel relocation. The channel position is generally stable in its present planform under current conditions.

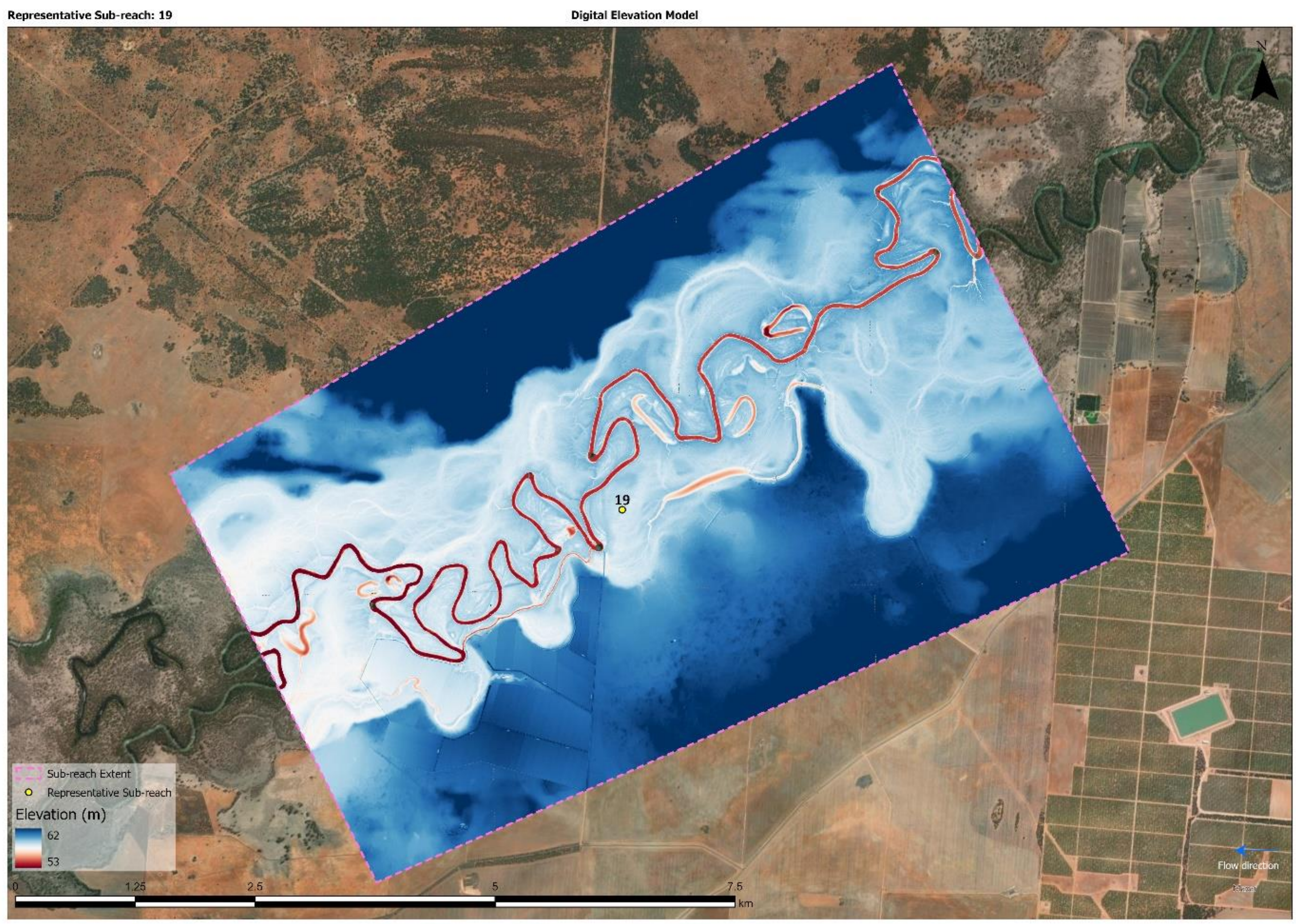

Figure 3 Historic imagery (circa 19xx) of the sub-reach extent

3. Floodplain form and process

e. Anthropogenic changes

Two areas in the left-bank floodplain have been cleared for cropping since the 1964 aerial photography. There are a few minor levees along the floodplain margin.

f. Hydrological connections

Low banks and and effluent channels allow flow from channel to floodplain. Channel capacity is 5,000 to 6,000 ML/d.

Low-lying parts of the floodplain (mostly partially infilled ancestral channels) may be inundated with flow of >7000 ML/D, however most do not appear to have hydrologic connection with the channel. Possibly they act as distal flood basins, only filling when the rest of the floodplain is inundated (>11,000 ML/D).

Along a 2 km stretch of the most tightly sinuous and convoluted channel (34.70° 143.42°), a flood runner connects the apex of two channel bends to the south-east of the channel. In the same reach, a diffuse flow path connects two other bends to the north-west of the channel: this is a low elevation infilled ancestral channel remnant, fed by an offtake channel from the upstream bend.

The floodplain will experience inundation for flows >7000 ML/d, and the shallow valley is likely to contain flows up to ~40,000 ML/d.

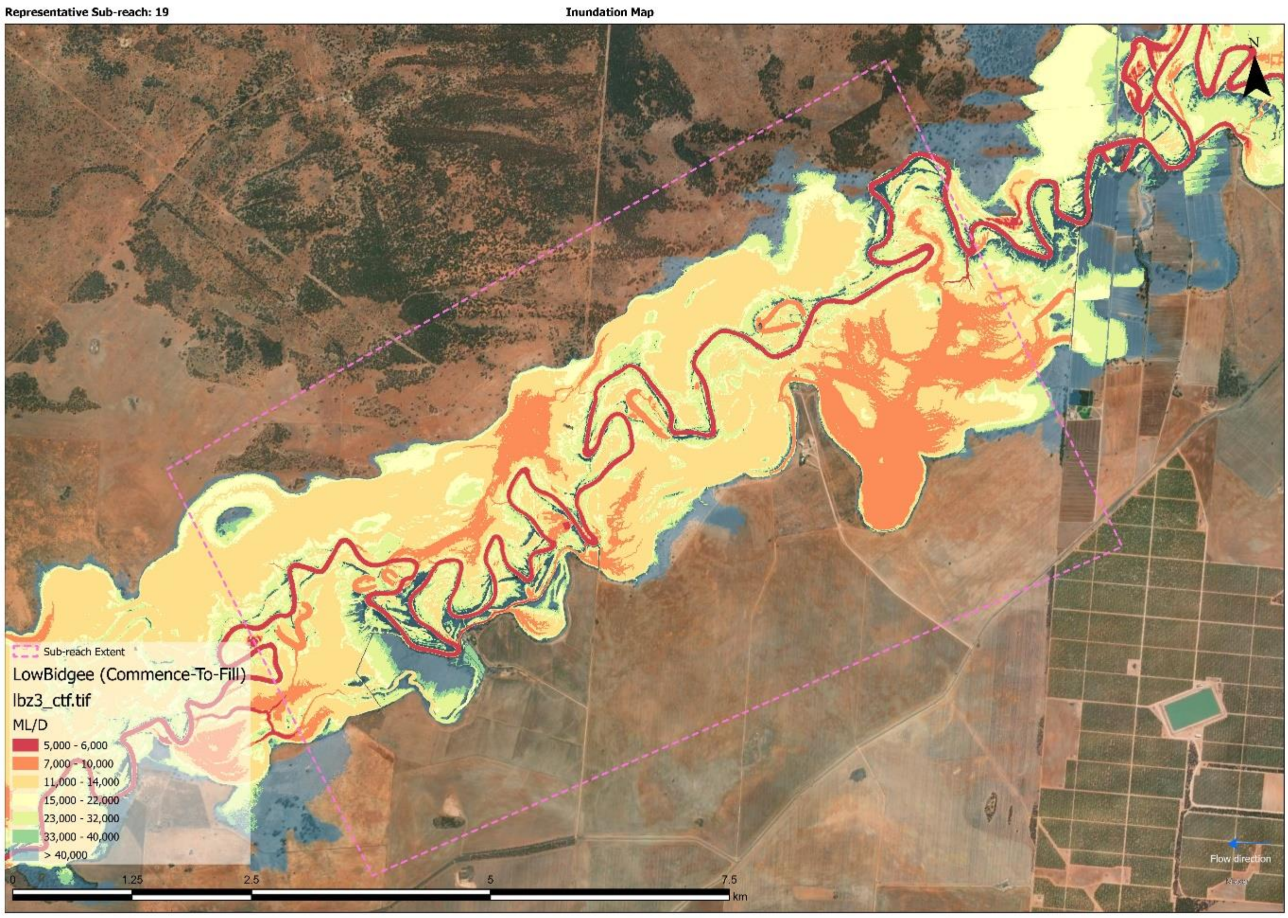

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

g. Landforms

Scroll plains are visible in some parts of the floodplain, but their ridge-and-swale topography is not very strongly expressed: it is best visible in the lidar. Partially infilled abandoned channel segments occur in the floodplain, most commonly where the present-day channel sinuosity is least convoluted.

There are traces of the ancestral river's infilled channel within the "black country" floodplain, e.g., in the west (-34.70° 143.40°) the lidar shows a shallow depression with clearly defined banks and levees. There are low points in the banks with short effluent channels, similar to those of the modern river.

h. Processes

It is likely the floodplain experiences inundation and vertical aggradation of fine sediment (evidence: infilling of abandoned channels and masking of scroll plains). It is probable that the floodplain has not experienced such inundation since the development of the weir (evidence: change of land-use).

At >7000 ML/d overbank flows and effluent channels deliver water to the floodplain, and inundation may occur in flood runners, abandoned channel loops, and the broad swales of partially-infilled ancestral channels.

lood-driven avulsion is likely to be the process that cuts across meanders. For example, the most tightly sinuous and convoluted channel (34.70° 143.42°) is not yet experienced meander cut-off. Here, landforms are in place which created the conditions predisposing flood-driven channel relocation. The present-day channel belt presents substantial barriers to in-channel flow (high sinuosity) and floodplain-level flow (dense vegetation;

landform elements oriented nearly perpendicular to downvalley flow direction). During floods (>27,000 ML/d), flows will encounter less roughness along both the flood runner and the diffuse flow path. Increased flow down either of these can initiate erosion, especially where floodwaters are confined between higher ground on one side and the slower flow on the other.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Floodplain (cutoffs)	Meander migration
Floodplain (anabranches)	Avulsion
Floodplain (> bankfull connection))	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 19 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This sub-reach receives flows from the Murrumbidgee River.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward RIver at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

We have completed the analysis based on the results at Balranald.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Cutoffs	Meander migration	1	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**0.82**	**0.74**	**0.44**	**0.35**	**0.31**
Likelihood (W40 events per year)		0.81	0.72	0.55	0.36	0.31
Likelihood (W32 events per year)		0.79	0.73	0.49	0.34	0.31

In its present regulated state, the channel is likely to remain stable (base case). Bankfull flows will partially inundate small areas within the floodplain, and larger flows will be required to water the wider floodplain. Even in its unregulated state, higher flows (≤40,000 ML/d) have minimal effect on the "red country". Local bank erosion due to the presence and operation of the weir could not be assessed in this desktop review due to the lack of available information. Any rapid changes in water levels because of regulation can impact bank stability.

Current conditions (base case) indicate a low energy environment with limited channel or floodplain change.

Under the flow options scenarios there is limited change in the flow regime across all flows in this sub-reach compared to current constraints except for bankfull flows. It is unlikely that for a low energy river such as this that the changes in flow regime will result in noticeable changes to the geomorphic features and processes above current rates of change.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Cutoffs	5.6	5.9	6%	5.7	2%
Floodplain (> bankfull)	2.0	2.0	2%	1.9	-1%
Anabranches / Floodrunners (> bankfull)	2.0	2.0	2%	1.9	-1%
Average	**3.2**	**3.3**	**4%**	**3.2**	**0%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Page, K.J, (1994) Late quaternary stratigraphy and chronology of the Riverine Plain, Southeastern Australia, PhD Thesis, University of Wollongong

Schumm, S.A. (1968). River Adjustment to Altered Hydrologic Regime – Murrumbidgee River and Paleochannels, Geological Survey Professional Paper 598, US Department of the Interior

Sub-Reach 20 Geomorphic Outline – Carrathool Reach

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The sub-reach is on the Murrumbidgee River, immediately downstream of Hay Weir, around 170 km from the confluence with the River Murray. The river is a major source of irrigation water and flow is heavily regulated, both by the two major dams, Burrinjuck and Blowering, and by a series of weirs, of which Hay weir is at the upstream end of this sub-reach.

2. Channel form and processes

a. Anthropogenic changes

The key changes that have impacted on the sub-reach (and lower Murrumbidgee more broadly) relate to land clearing since European settlement, and altered hydrology through the construction of dams and storages, flow diversion for irrigation and the associated infrastructure (weirs, diversion channels etc.). Land use change in the catchment caused an increase in headwater gullying and consequent rise in sediment loads within the Murrumbidgee (Olley and Scott 2002), however the construction of the Hay Weir has effectively cut off the supply of coarse (sand and gravel) sediment.

b. Historic changes based on the historical imagery

There were no observable changes in channel position in this section of the Murrumbidgee between the 1968 black and white aerial photographs and the 2021 Maxar satellite imagery, aside from the creation of the weir pool since the construction of Hay Weir. There has been a minor an increase in the extent and of riparian and floodplain canopy cover in the upstream half of the sub-reach. The resolution of the historic imagery does now allow for an assessment of instream wood loads or bar forms.

c. Forms (mainly based on LiDAR)

This section of the Murrumbidgee River is described in the RiverStyles data as a laterally unconfined, meandering, continuous channel with a fine-grained bed. The section within sub-reach 20 has a sinuosity ratio of 1.7. There are multiple oxbow lakes which have their own small tributaries. There are no sub-bankfull connections to floodplain.

a. Processes

The dominant processes affecting channel form in this sub-reach are likely related to changes in discharge brought by regulation, and a reduction in coarse sediment due to the upstream weir. High flows during summer (when they would normally be low) can cause erosion and hamper vegetation recruitment and growth, typically leading to a decline in bank condition and ultimately channel widening. With reduced sediment supply bank repair is also less likely. Wallbrink et al. (1997) demonstrated that most (>80%) of the sediment in transport in the lower river was derived from the erosion of channel banks and gully walls.

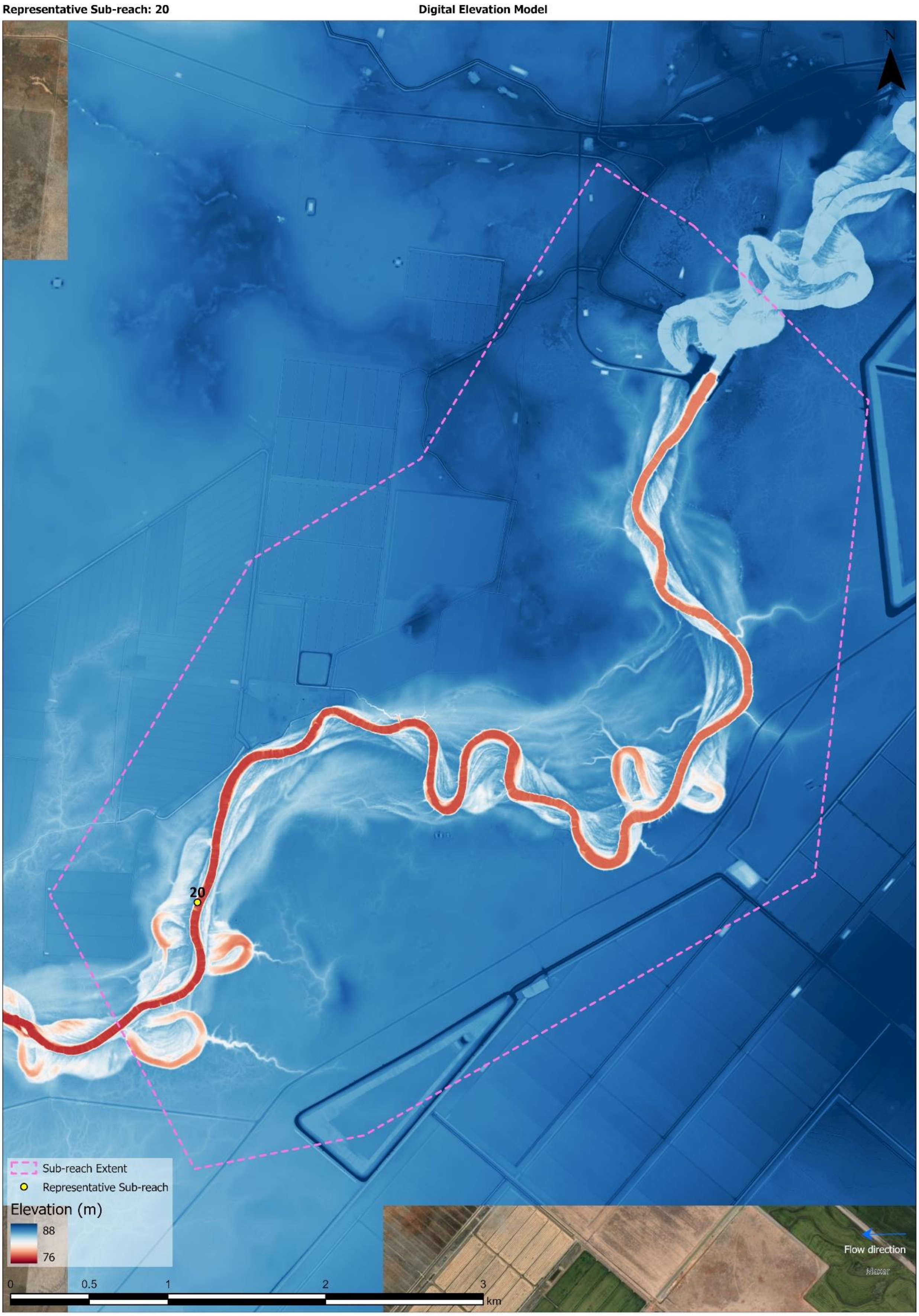

Figure 2. Lidar DEM of sub-reach 20.

3. Floodplain form and process

b. Anthropogenic changes

The key anthropogenic changes to the floodplain area include land clearing, however, there has been a more recent increase in the extent and density of floodplain forest cover (in the upstream half of the sub-reach) since the 1968 historic imagery as captured. Irrigation channels supplying agriculture in the area, and road construction on the nearby floodplain, have like altered overland flow for the sub-reach.

c. Hydrological connections

Connection to the floodplain within the sub-reach is limited, with no sub-bankfull connections. There are several small tributary gullies that would be inundated during >bankfull flows, as would a large area of floodplain in the east of the sub-reach (Figure 2).

d. Form (mainly based on LiDAR)

The floodplain of the lower Murrumbidgee (of which sub-reach 20 is a part) is marked by a large number of relict channels and billabongs. There is considerable retention of water on the floodplain and much of the water which leaves the channel during floods is not returned to the river when the flood waters recede (Olley and Scott 2000).

e. Processes

The processes of erosion and deposition on the floodplain are a balance between the length and rate of flow, the sediment volumes delivered in the flows and the vegetation. Infrequent inundation (due to the highly regulated nature of the system and limited channel-floodplain connections) mean that rates of change will be low. Artificial structures like levees and roadways will also act to constrain where deposition and erosion will occur during >bankfull events.

Representative Sub-reach: 20 **Inundation Map**

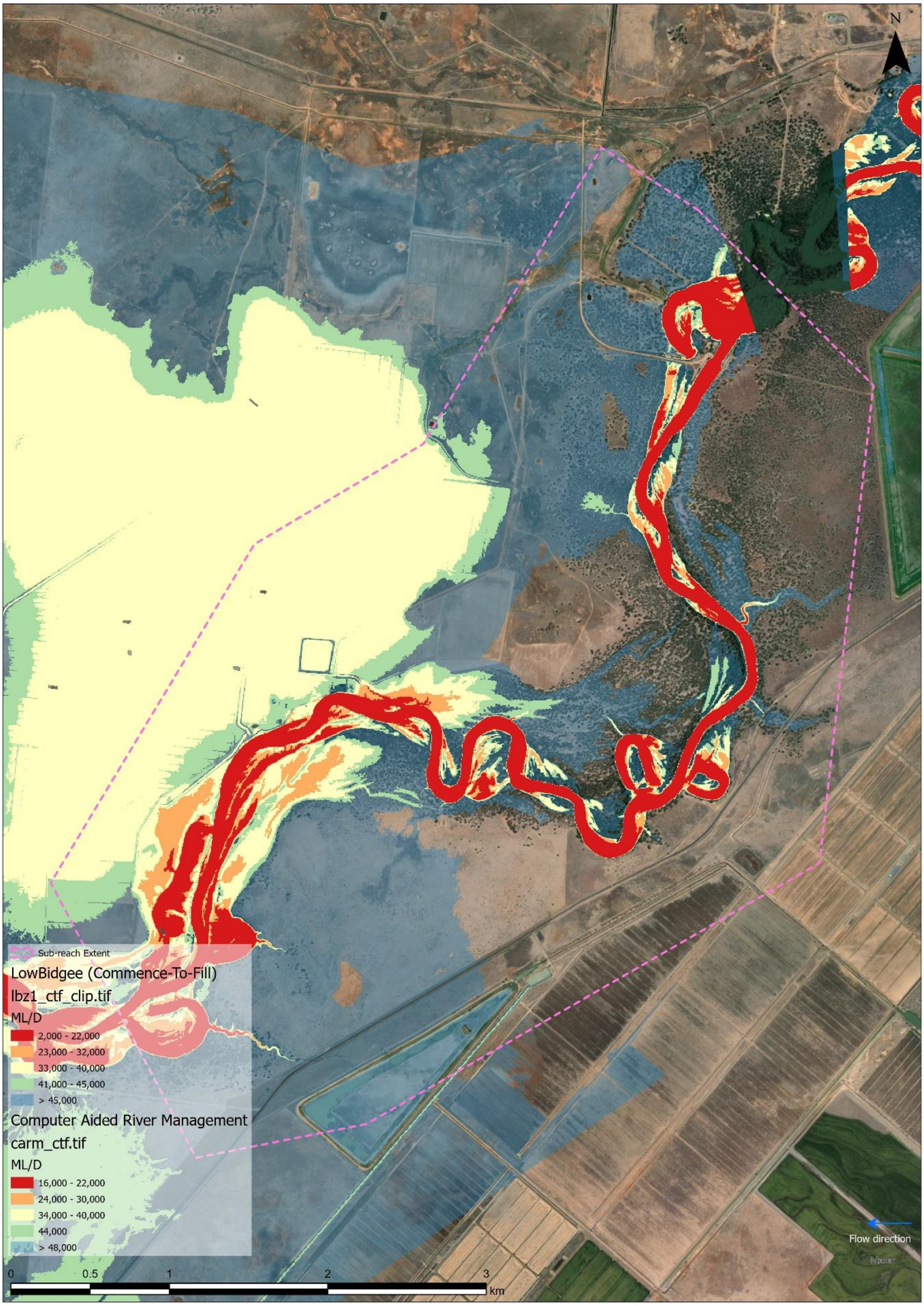

Figure 3. Inundation map for sub-reach 20.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 20 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This sub-reach receives flows from the Murrumbidgee River.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbank	Erosion	3	2	1	1	1
Cutoffs	Meander migration	1	2	3	3	3
Floodplain (sub-bankfull - anabranch / floodrunners)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**0.92**	**0.70**	**0.58**	**0.33**	**0.21**
Likelihood (W40 events per year)		0.92	0.69	0.63	0.31	0.21
Likelihood (W32 events per year)		0.89	0.71	0.66	0.32	0.21

It is likely that prolonged, constant flows will result in notching of the banks through this section which combined with the loss of vegetation from the lower banks, will reduce the ability of these banks to withstand future peaked or prolonged flow events. Erosion can also be enhanced in locations where there is a rapid change in flow such as upstream and downstream of weirs or regulating structures.

Under the flow options scenarios minimal to no geomorphic changes are expected.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbank	5.3	5.3	0%	5.3	0%
Cutoffs	5.7	5.8	1%	5.9	3%
Floodplain (sub-bankfull - anabranch / floodrunners)	4.8	4.8	2%	5.0	4%
Floodplain (> bankfull)	1.6	1.6	-3%	1.6	-3%
Anabranches / Floodrunners (> bankfull)	1.6	1.6	-3%	1.6	-3%
Average	**3.8**	**3.8**	**0%**	**3.9**	**1%**

6. Limitations and Constraints

Key limitations regarding this sub-reach related to a lack of data on channel form and processes. Therefore, inferences have been made based on what is known about the Lower Murrumbidgee more generally, of which this sub-reach is a part.

7. References

MDBA. (2012). *Assessment of environmental water requirements for the proposed Basin Plan: Lower Murrumbidgee River (in-channel flows).* MDBA Publication No: 42/12.

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Wallbrink, P.J., Olley, J.M., Murray, A.S., and Olive, L.J. (1998). *Determining sediment sources and transit times of suspended sediment in the Murrumbidgee River, NSW, Australia using fallout* ^{137}Cs *and* ^{210}Pb. Water Resources Research 34, 879-887.

Sub-Reach 21 Geomorphic Outline – Narrandera Reach

Figure 1 Sub-reach map extent

1. Sub- reach position in catchment and general description

The sub-reach is on the Murrumbidgee River approximately 26km downstream of the offtake with Yanco Creek and is confined by the earlier Murrumbidgee paleochannel. Part of the channel and floodplain are within the Murrumbidgee Valley National Park. Page and Nanson (1996) describe this area as having substantial floodplain development with large meander cut-offs from palaeo-floodplain (floodplain width 2-6 km). Gogeldrie Weir is located at the upstream end of the sub-reach.

The Tom Bullen Storage sits on the left-hand floodplain where there had previously been a swamp. It is about 10 south west of Gogeldrie Weir and is fed by an inlet channel from the Coleambally Canal. It discharges into the Murrumbidgee through a single channel (Tombullen Creek). It is 11,933 ML in capacity and is designed to facilitate the recovery of wetland vegetation in a number of mid-Murrumbidgee wetlands.

The majority of the channel has been classed as Laterally Unconfined Sinuous Fine Grained by the RiverStyles assessments. These assessments also suggest the river is in moderate condition and has low fragility with a high recovery potential.

2. Channel form and processes

a. Anthropogenic changes

The Gogeldrie Weir, built 1958-1959, diverts water into the Coleambally Canal and the Stuart Canal via the Coononcoocabil Lagoon. It has a maximum capacity of 4,471.5 ML (SKM, 2011).

b. Historic changes based on the historical imagery

There appears to be sections where the bed is completely dry in 1945. Based on the colour and homogeneous nature of the bed they appear to be a sheets of sand, and may represent pulses of sediment moving downstream.

There has been an Increase in floodplain vegetation since 1945 and also an increase in instream large wood.

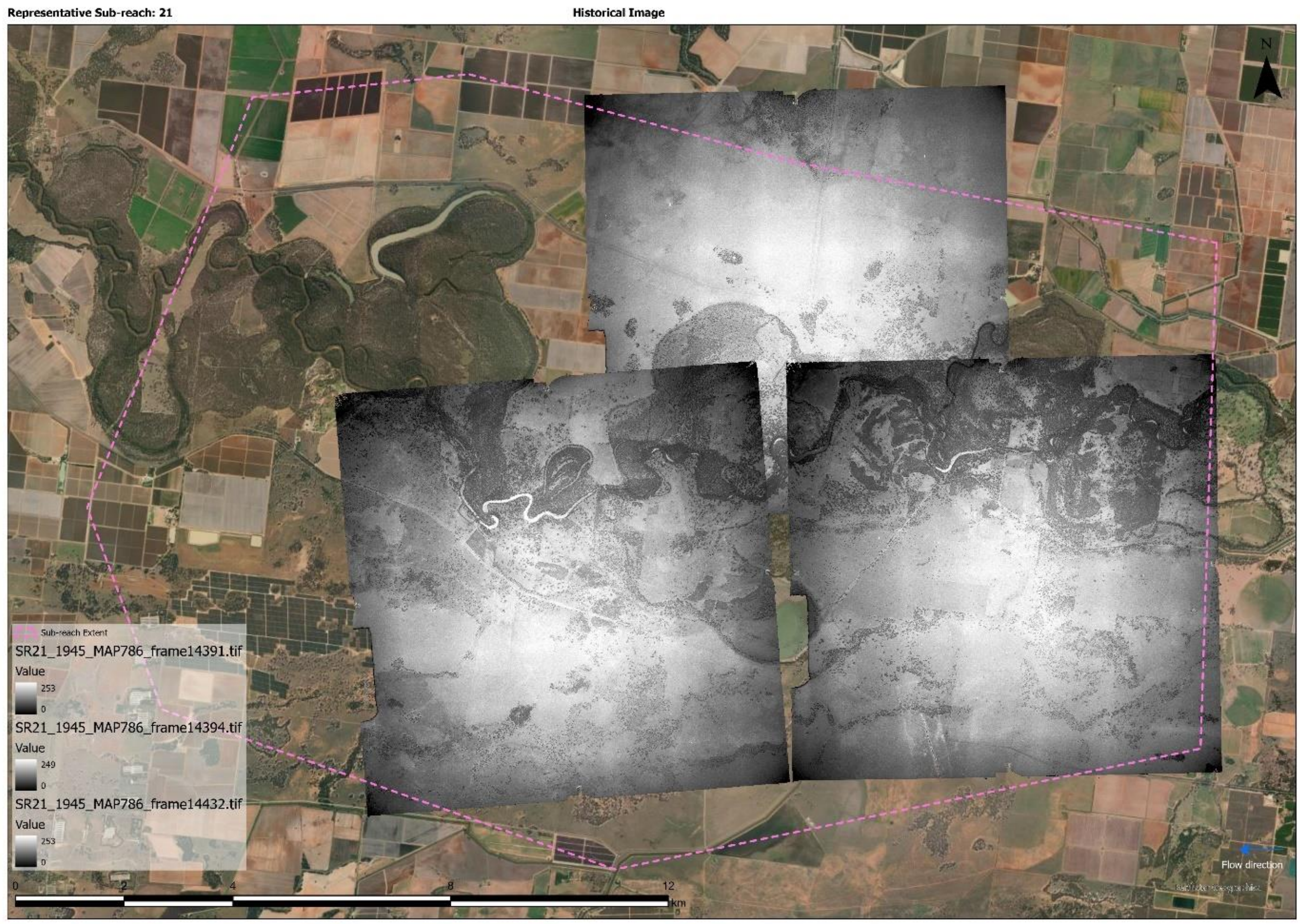

Figure 2 Historic imagery (circa 19xx) of the sub-reach extent

c. Forms (mainly based on LiDAR)

A meandering channel with steep bare banks on the outer bends. There is limited evidence of mass failure scars, however, curvilinear features on the riverbank suggest that they do occur. The exact mechanism of failure cannot be determined. Bank erosion appears to be dominated by fluvial entrainment based on the smooth and steep shape of the riverbanks.

Small sandy point bar deposits appear at most bends. For example, Macca's Beach is identified on google maps as a site within this reach and online photos indicate a significant sandy point bar is present at this location. Erskine et al (1992) noted the presence of sandy point bars in this sub-reach with a median grain size of 0.25 to 4mm. Additionally, the presence of instream sand also looks extensive on the channel bed in the current imagery, with dune structures similar to those observed in the Barmah Choke from Tocumwal to Picnic Point. Olley and Scott (2002) noted that in Murrumbidgee River downstream of Wagga Wagga there are large sand deposits in the channel.

d. Processes

There appears to be some evidence of mass failures on the riverbanks, however, the mechanism of failure is unclear based on the LiDAR and aerial imagery. The main form of riverbank erosion is assumed to be fluvial entrainment. Lateral accretion is occurring to form the point bars on the inside of the bends.

Due to the regulated flow conditions in the Murrumbidgee River sediment transport is dominated by storm events, with larger events in winter and spring. Sediment loads during the irrigation season tend to be low. Most of this sediment load originates from tributaries rather than from channel erosion (Olive and Olley, 1997). Overall, the irrigation system is designed to abstract water rather than sediment and a smaller proportion of sediment is removed compared to water resulting in a depositional environment, evidenced by the increasing prevalence of sandy point bars and sand sheets present in the channel through this sub-reach.

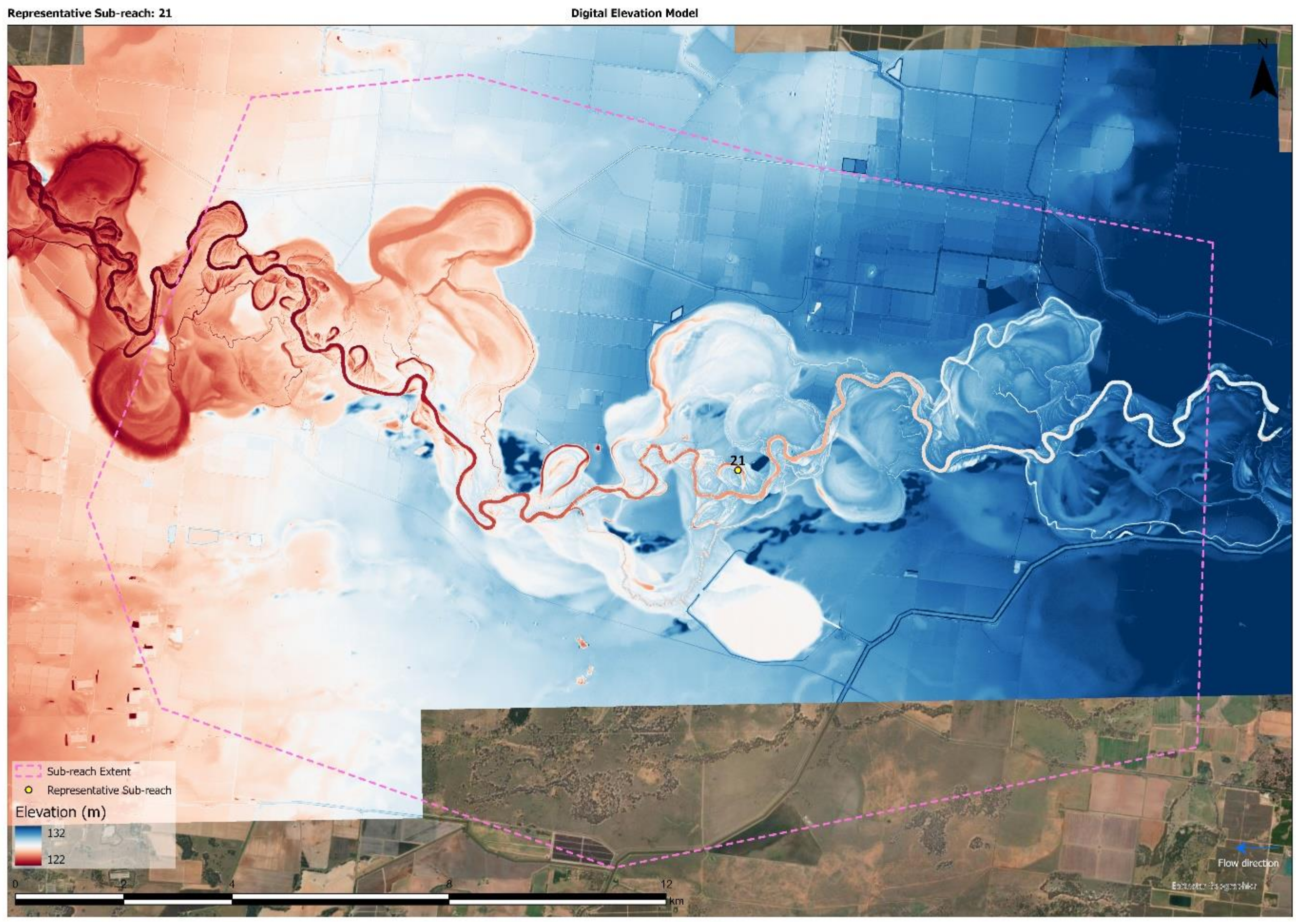

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

3. Floodplain form and process

a. Anthropogenic changes

The Tombullen Storage has been created by building levees around a swamp on the wetland. There are also levees along the floodplain margin defining the boundary between the floodplain and adjacent agricultural land.

b. Historic changes based on the historical imagery

There has been an increase in floodplain vegetation from 1945 and more unsealed roads. The extent of irrigated agricultural land, along with levees and channels has increased substantially north and south of the river.

c. Hydrological connections

Inundation map shows inundation of small floodplain channels, billabongs and swales at 16,000 – 22,000 ML/d. The Euwarderry Lagoon was connected at a flow of 24,500 ML/d (SKM 2011).

d. Form (mainly based on LiDAR)

Ox bow – Billabongs, meander scrolls, small anabranch channels and flood channels ending in splays. There is some defined pinnate drainage on the floodplain.

e. Processes

As noted by Page et al (2003) most of the floodplain sediment on the lower Murumbidgee river has formed through oblique accretion which is "*the lateral accumulation of fine-grained floodplain sediemnt by progradation of relatively steep convex banks associated with channel migration*." However, the rate of lateral channel migration is low (Owens, 1998) and Page et al (2003) found that the vertical accretion rate on the floodplain was also low.

The channel ending in a splay that is across Euwarderry Lagoon may be a developing anabranch channel. A comparison of lidar terrain models from 2009 to 2020 indicates that there may be some erosion and deposition along this channel.

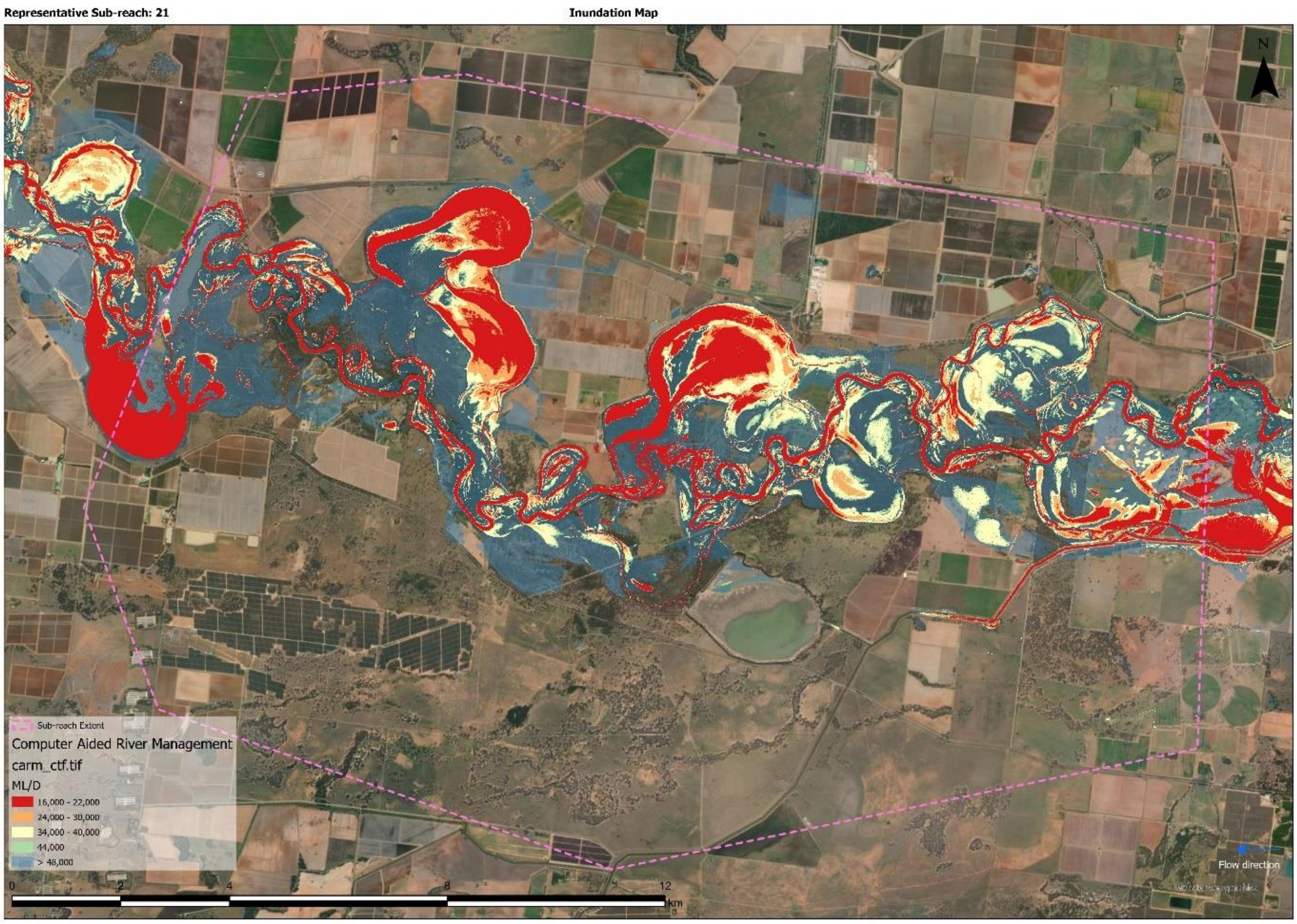

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

4. Base case

The base case geomorphic features and processes are summarised in *Table 1*.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 20 are summarised in *Table 3*. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This sub-reach receives flows from the Murrumbidgee River.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbank	Erosion	3	2	1	1	1
Cutoffs	Meander migration	1	2	3	3	3
Floodplain (sub-bankfull - anabranch / floodrunners)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.83**	**0.23**	**0.19**	**0.06**
Likelihood (W40 events per year)		1.00	0.80	0.21	0.17	0.05
Likelihood (W32 events per year)		1.00	0.81	0.22	0.18	0.05

The inherent imbalance between flow and sediment transport because of regulated flow delivering irrigation water means that the sub-reach and much of the Murrumbidgee downstream of Wagga Wagga is an increasingly depositional environment in-channel. This is evidenced by the visible sandy point bars and what appears to be sand sheets within the channel.

Floodplain inundation remains within the paleo-floodplain (floodplain width 2-6 km) but is increasingly constrained in places by levees and channels.

It is likely that prolonged, regulated flows will result in notching of the banks through this section which combined with the loss of vegetation from the lower banks, will reduce the ability of these banks to withstand future peaked or prolonged flow events.

Under the flow options scenarios there are negligible changes to the various flow categories. Only flows at or around the bankfull category are predicted to occur with (marginally) increased frequency, and any changes to the rates of geomorphic processes in this sub-reach are expected to be similar to current rates of change.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbank	5.1	5.0	-2%	5.1	-1%
Cutoffs	4.1	3.9	-6%	4.0	-3%
Floodplain (sub-bankfull - anabranch / floodrunners)	3.1	2.9	-8%	3.0	-4%
Floodplain (> bankfull)	0.8	0.7	-14%	0.7	-6%
Anabranches / Floodrunners (> bankfull)	0.8	0.7	-14%	0.7	-6%
Average	**2.8**	**2.6**	**-5%**	**2.7**	**-3%**

6. Limitations and Constraints

This desktop assessment is based on available studies and data, limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

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Olive, L.J. and Olley, J.M. (1997). River regulation and sediment transport in a semiarid river: the Murrumbidgee River, New South Wales, Australia, Human Impacts on Erosion and Sedimentation, Proceedings of Rabat Symposium S6, IAHS Publication No. 245

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Sinclair Knight Merz (2011). *Environmental Water Delivery: Murrumbidgee Valley.* Prepared for Commonwealth Environmental Water, Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Sub-Reach 22 Geomorphic Outline – Yanco Creek (at Murrumbidgee)

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

Yanco Creek is an effluent of the Murrumbidgee River and leaves the river near Narrandera and flows 800 kilometres south to Morundah then south-west to join Billabong Creek at Conargo. The main regulating structure is Yanco Weir on the Murrumbidgee, with flows into Yanco Creek controlled an offtake structure that limits flow to 1,400 ML/d (DPI 2018). Yanco Weir is one of multiple that provide the head necessary to supply irrigation areas and effluents such as the Yanco Creek.

The Yanco Creek system supplies water to a number of towns including Morundah, Urana, Oaklands, Jerilderie, Conargo, Wanganella and Moulamein. The system also provides water to many private irrigators. The supply of regulated flow through the creek system for over a century has resulted in the development of a diverse agricultural industry of winter cereals and summer crops (DPI 2018).

2. Channel form and processes

a. Anthropogenic changes

Prior to European settlement, Yanco Creek was a high-level effluent creek, and it is believed that the Murrumbidgee River only connected to the creek during flows of around 40,000 ML/day or greater (DPI 2015). In the late 1800s a cutting was made to provide flows at lower levels. The Yanco Weir on the Murrumbidgee River was built in 1928 and upgraded in 1981 to control and increase flows into the creek system (DPI 2015). The Yanco Creek system is now a permanently flowing one and supports a number of fish species and other biota, many of which have declined in other parts of the system (DPIE 2020).

b. Historic changes based on the historical imagery

There were no observable changes in channel position in this section of Yanco Creek between the 2021 Maxar satellite imagery and the 1945 black and white aerial photographs (which come after the 1928 construction of Yanco Weir). There has been a minor an increase in the extent and of riparian canopy cover. The resolution of the historic imagery does now allow for an assessment of instream wood loads or bar forms.

c. Forms (mainly based on LiDAR)

This sub-reach is an anbranching system that includes Yanco Creek, and several sub-branches including Back Creek, Washpen Creek and Pine Creek, that eventually re-join Yanco Creek downstream (in sub-reach 23). Yanco Creek and Washpen Creeks are described in the RiverStyles data as a laterally unconfined, continuous channel, low sinuosity, fine grained bed. The Back Creek anabranch is the same although meandering, while the Pine Creek anabranch is terrace constrained with a gravel bed. There are multiple oxbow lakes, wetlands, and effluent connections to the floodplain.

a. Processes

The dominant processes affecting channel form in this sub-reach are undoubtedly related to changes in discharge brought by regulation, in particular the creation of Yanco Weir pool on the Murrumbidgee that means the creek now carries water year-round, instead of only during floods.

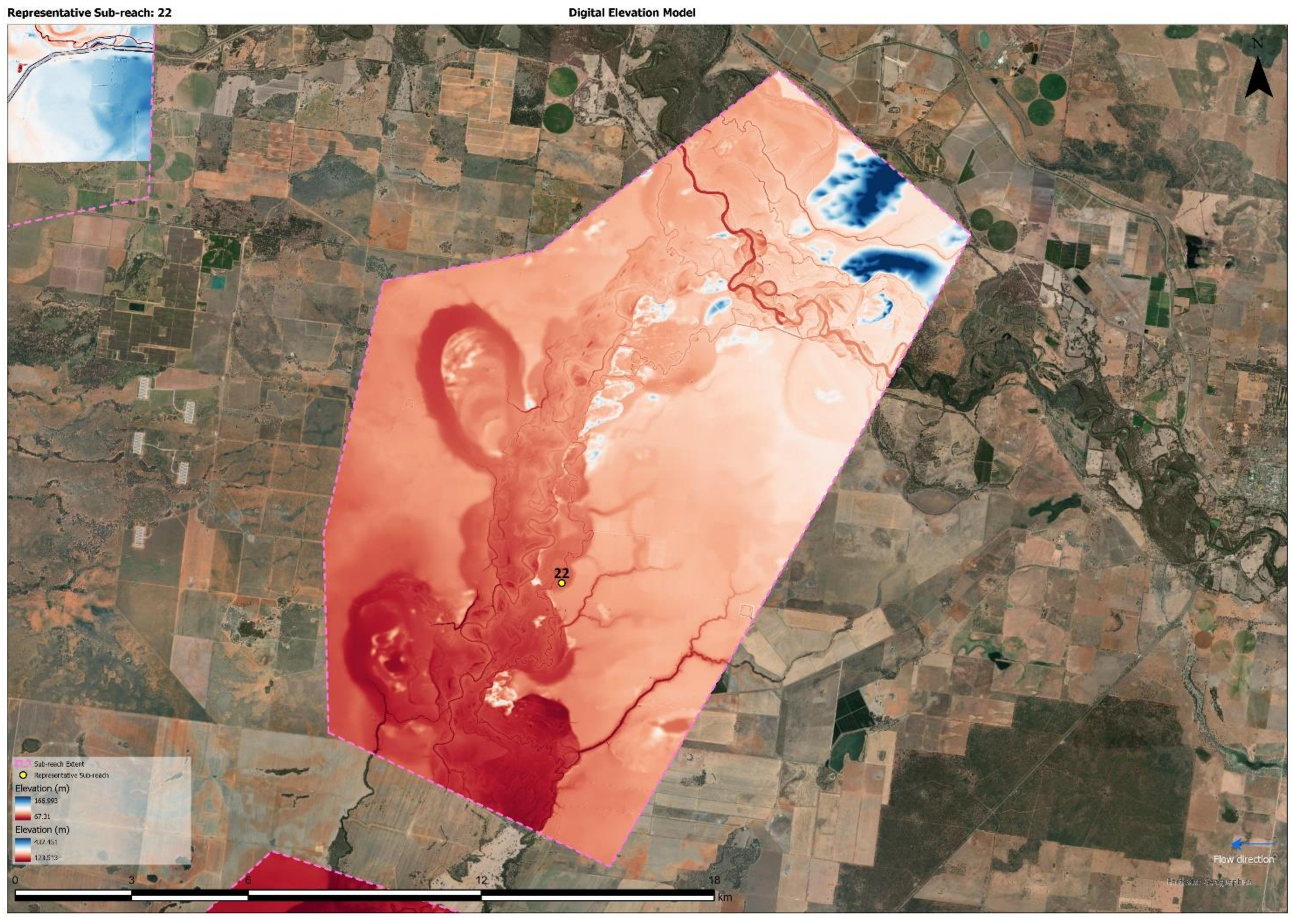

Figure 2. Lidar DEM of sub-reach 22.

3. Floodplain form and process

b. Anthropogenic changes

The key anthropogenic changes to the floodplain area include land clearing, however, there has been a more recent increase in the density of riparian forest cover since the 1945 historic imagery was captured. Irrigation channels supplying water for agriculture and townships in the area, and road construction on the nearby floodplain, have like altered overland flow for the sub-reach.

c. Hydrological connections

Connection to the floodplain within the sub-reach is common, at least in the northern half of the sub-reach in which inundation data is available (Figure 2). As this is part of an anabranching system, it is likely that the channel is also well connected to its floodplain in the southern half of the sub-reach.

d. Form (mainly based on LiDAR)

The floodplain of this sub-reach is marked by a large number of relict channels and billabongs.

e. Processes

The processes of erosion and deposition on the floodplain are a balance between the length and rate of flow, the sediment volumes delivered in the flows and the vegetation. Infrequent inundation (due to the highly regulated nature of the system and limited channel-floodplain connections) mean that rates of change will be low. Artificial structures like levees and roadways will also act to constrain where deposition and erosion will occur during >bankfull events.

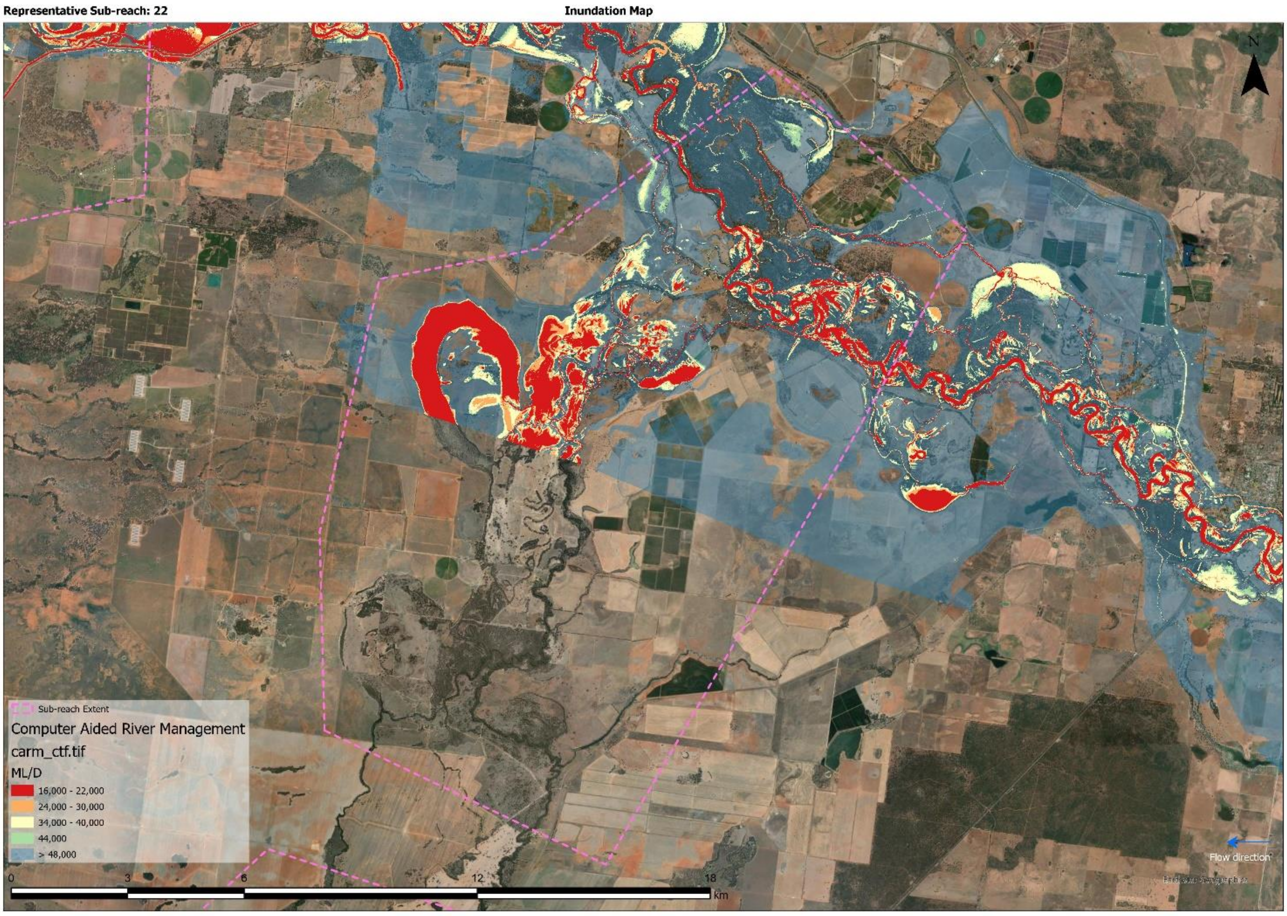

Figure 3. Inundation map for sub-reach 22.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., large freshes or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 22 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This sub-reach receives flows from the Murrumbidgee River.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbank	Erosion	3	2	1	1	1
Cutoffs	Meander migration	1	2	3	3	3
Floodplain (sub-bankfull - anabranch / floodrunners)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**0.80**	**0.63**	**0.49**	**0.35**	**0.15**
Likelihood (W40 events per year)		0.77	0.66	0.60	0.36	0.15
Likelihood (W32 events per year)		0.76	0.67	0.56	0.34	0.15

It is likely that constant prolonged flows do or could result in notching of the banks through this section. Erosion can also be enhanced in locations where there is a rapid change in flow such as upstream and downstream of weirs or regulating structures.

Under the flow options scenarios flows within the large fresh and bankfull category are likely to occur with increased frequency, which may enhance the potential for lateral migration and associated bank erosion processes although the rates of change are expected to be low.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbank	4.7	4.7	2%	4.7	0%
Cutoffs	5.0	5.4	7%	5.3	5%
Floodplain (sub-bankfull - anabranch / floodrunners)	4.2	4.7	9%	4.5	7%
Floodplain (> bankfull)	1.5	1.5	1%	1.5	-2%
Anabranches / Floodrunners (> bankfull)	1.5	1.5	1%	1.5	-2%
Average	**3.4**	**3.6**	**5%**	**3.5**	**3%**

6. Limitations and Constraints

Key limitations regarding this sub-reach related to a lack of data on channel form and processes. Therefore, inferences have been made based on what is known about the Lower Murrumbidgee more generally, of which this sub-reach is a part.

7. References

DoI. (2019). *Risk Assessment for the Murrumbidgee Water Resource Plan Area (SW9): Part 1.* Report by NSW Department of Industry: Water, May 2019.

DPI. (2015). *Improved flow management works at the Murrumbidgee Rivers – Yanco Creek offtake. SDL Adjustment Business Case*. Report by NSW Department of Primary Industries, August 2015.

DPI. (2018). *Murrumbidgee Water Resource Plan: Surface water resource description*. Report by NSW Department of Primary Industries: Water, April 2018.

DPIE. (2020). *Murrumbidgee Long Term Water Plan Part A: Murrumbidgee catchment.* Report by the NSW Department of Planning, Industry and Environment, July 2020.

streamology

Sub-Reach 22 Geomorphic Outline – Yanco Creek and Colombo Creek

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

This sub-reach encompasses a part of the Yanco Creek system, which is an effluent of the Murrumbidgee River. Within the sub-reach is Yanco Creek and its anabranch, Colombo Creek. The main regulating structure for the broader Yanco system is Yanco Weir on the Murrumbidgee, with flows into Yanco Creek controlled by an offtake structure that limits flow to 1,400 ML/d (DPI 2018). Yanco Weir is one of multiple that provide the head necessary to supply irrigation areas and effluents such as the Yanco Creek. Tarabah Weir near Morundah diverts water from Yanco Creek into Colombo Creek which flows south-east through open plains to join Billabong Creek upstream of Jerilderie (DPI 2018).

The Yanco Creek system supplies water to a number of towns including Morundah, Urana, Oaklands, Jerilderie, Conargo, Wanganella and Moulamein. The system also provides water to many private irrigators. The supply of regulated flow through the creek system for over a century has resulted in the development of a diverse agricultural industry of winter cereals and summer crops (DPI 2018).

2. Channel form and processes

a. Anthropogenic changes

Prior to European settlement, Yanco Creek was a high-level effluent creek and it is believed that the Murrumbidgee River only connected to the creek during flows of around 40,000 ML/day or greater (DPI 2015). In the late 1800s a cutting was made to provide flows at lower levels. The Yanco Weir on the Murrumbidgee River was built in 1928 and upgraded in 1981 to control and increase flows into the creek system (DPI 2015). The Yanco Creek system is now a permanently flowing one and supports a number of fish species and other biota, many of which have declined in other parts of the system (DPIE 2020).

b. Historic changes based on the historical imagery

There were no observable changes in channel position in this section of Yanco Creek or Colombo Creek between the 2021 Maxar satellite imagery and the 1968 black and white aerial photographs (which come after the 1928 construction of Yanco Weir). There has been a minor decrease in the extent and of riparian canopy cover in some areas. The resolution of the historic imagery does now allow for an assessment of instream wood loads or bar forms.

c. Forms (mainly based on LiDAR)

This sub-reach is an anbranching system that includes Yanco Creek, and several sub-branches including Back Creek, Washpen Creek and Pine Creek, as well as Colombo Creek, which branches off Yanco to flow south-east and eventually join Billabing Creek (beyond sub-reach 23). Yanco, Colombo, and Washpen Creeks are described in the RiverStyles data as a laterally unconfined, continuous channel, low sinuosity, fine grained bed. The Pine Creek anabranch is terrace constrained with a gravel bed. There are multiple oxbow lakes, wetlands and effluent connections to the floodplain throughout this sub-reach.

a. Processes

The dominant processes affecting channel form in this sub-reach are undoubtedly related to changes in discharge brought by regulation, in particular the creation of Yanco Weir pool on the Murrumbidgee that means the system now carries water year-round, and the Tarabah Weir which diverts water from Yanco Creek into Colombo Creek.

One small anabranch near Morundah, named Cheverells Creek, branches from Colombo Creek downstream from where the Yanco and Colombo Creeks split. Flows enter Cheverells Creek through a culvert under Yamma Road that only allows up to 10 ML/day. With a very high Colombo Creek the flows would overtop the road into Cheverells Creek, only for flows far higher than flow options flows.

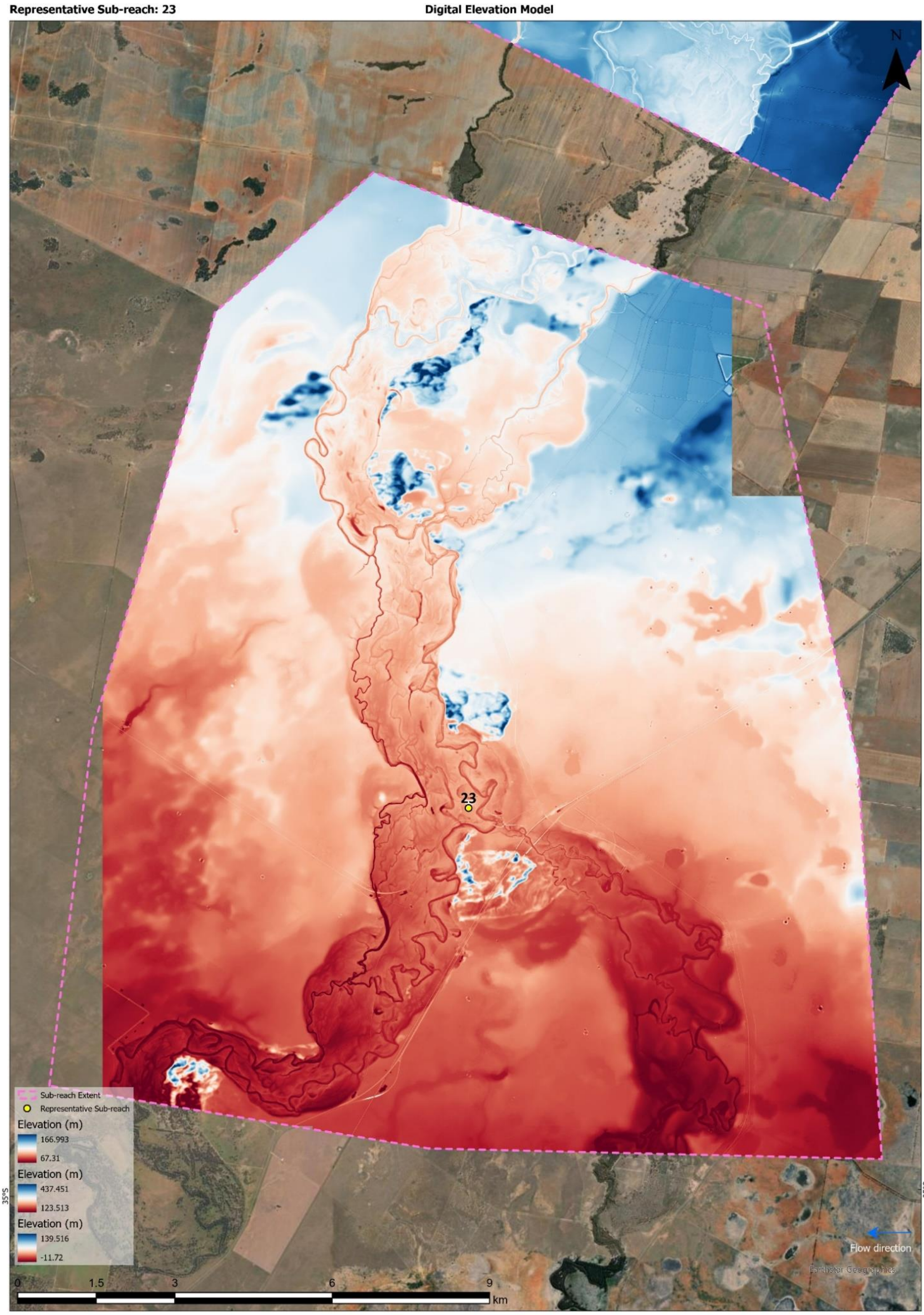

Figure 2. Lidar DEM of sub-reach 22.

3. Floodplain form and process

b. Anthropogenic changes

The key anthropogenic changes to the floodplain area include land clearing. Irrigation channels supplying water for agriculture and townships in the area, and road construction on the nearby floodplain, have like altered overland flow for the sub-reach.

c. Hydrological connections

Connection to the floodplain within the sub-reach appear common when examining the lidar data, and being an anabranching system, it is likely that the channel is well connected to its floodplain although this is controlled by the weirs. However, no inundation data is available for this sub-reach, so determining the nature of those connections (sub-bankfull or >bankfull) is difficult.

d. Form (mainly based on LiDAR)

The floodplain of this sub-reach is marked by a large number of relict channels and billabongs.

e. Processes

The processes of erosion and deposition on the floodplain are a balance between the length and rate of flow, the sediment volumes delivered in the flows and the vegetation. Infrequent inundation (due to the highly regulated nature of the system and limited channel-floodplain connections) mean that rates of change will be low. Artificial structures like levees and roadways will also act to constrain where deposition and erosion will occur during >bankfull events.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic Features and Processes

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Meander migration
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull – anabranches/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 23 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to this reach are as follows. This sub-reach receives flows from the Murrumbidgee River.

Table 2   Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations					
		Regulated Flows	Sub-bankfull flows (freshes)	Sub-bankfull (high flow freshes)	Bankfull	Bankfull floodplain flow	Large floodplain inundation events
Riverbank	Erosion	3	3	2	1	1	1
Cutoffs	Meander migration	1	1	2	3	3	3
Floodplain (sub-bankfull - anabranch / floodrunners)	Avulsion	1	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	0	3	3
Likelihood (current constraints events/yr)		**0.92**	**0.92**	**0.70**	**0.58**	**0.33**	**0.21**
Likelihood (W40 events per year)		0.92	0.92	0.69	0.63	0.31	0.21
Likelihood (W32 events per year)		0.92	0.89	0.71	0.66	0.32	0.21

It is likely that constant prolonged flows do or could result in notching of the banks through this section. Erosion can also be enhanced in locations where there is a rapid change in flow such as upstream and downstream of weirs or regulating structures.

Under the flow options scenarios flows within the large fresh and bankfull category are likely to occur with increased frequency, which may enhance the potential for lateral migration and associated bank erosion processes although the rates of change are expected to be low.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbank	4.7	4.7	2%	4.7	0%
Cutoffs	5.0	5.4	7%	5.3	5%
Floodplain (sub-bankfull - anabranch / floodrunners)	4.2	4.7	9%	4.5	7%
Floodplain (> bankfull)	1.5	1.5	1%	1.5	-2%
Anabranches / Floodrunners (> bankfull)	1.5	1.5	1%	1.5	-2%
Average	**3.4**	**3.6**	**5%**	**3.5**	**3%**

6. Limitations and Constraints

Key limitations regarding this sub-reach related to a lack of data on channel form and processes. Therefore, inferences have been made based on what is known about the Lower Murrumbidgee more generally, of which this sub-reach is a part.

7. References

DoI. (2019). *Risk Assessment for the Murrumbidgee Water Resource Plan Area (SW9): Part 1.* Report by NSW Department of Industry: Water, May 2019.

DPI. (2015). *Improved flow management works at the Murrumbidgee Rivers – Yanco Creek offtake. SDL Adjustment Business Case*. Report by NSW Department of Primary Industries, August 2015.

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DPIE. (2020). *Murrumbidgee Long Term Water Plan Part A: Murrumbidgee catchment.* Report by the NSW Department of Planning, Industry and Environment, July 2020.

Sub-Reaches 24 (d/s) and 25 (u/s) Geomorphic Outline – Mid Murrumbidgee Reach

Figure 1 Sub-reach map extent (sub-reach 24)

Figure 2 Sub-reach map extent (sub-reach 25)

1. Sub-reach position in catchment and general description

Sub-reach 24 is on the Murrumbidgee River approximately 75km upstream of the town of Narrandera. The reach length is approximately 38km. The reach is dominated by an extensive floodplain extending between 2 to 8km wide and includes both the Old Man Creek and Bundidgerry Creek Anabranches. Berembed Weir is located about 13km from the start of this reach and control flows to both downstream of the Murrumbidgee and the Bundidgerry Creek anabranch.

Sub-reaches 25 is located on the Murrumbidgee River approximately 25km downstream of the town of Wagga Wagga. The reach length is approximately 65km. The reach is dominated by an extensive floodplain extending between 2 to 8km wide and includes both the Old Man Creek and Beavers Creek Anabranches. Murrumbidgee Valley National Park is located in the middle section of this reach with some sections of the Beavers Creek Anabranch running through or bordering it.

2. Channel form and processes

a. Anthropogenic Influences

Water storage infrastructure upstream of the reach will have had the most significant impact on the reach through changes to sediment budget along with flow seasonality, variability, and duration. Tanangara Reservoir and Burrinjuck Dam are located upstream of site. Other water storages on the tributaries upstream include Happy Jacks Dam, Tumut Pond Dam, Tumut Two Dam, Talbingo Dam, Jounama Dam, and Blowering Dam, Corin Dam, Bindura Dam and Cotter Dam.

Sub-reach 24

Berembed weir is located on the confluence of Murrumbidgee River and the Bundidgerry Creek Anabranch. It appears that an irrigation channel has been cut through along with sections of the Bundidgerry Creek anabranch as sections of the channels are very straight.

Buckingbong Road crosses Old Man Creek anabranch at the lower end of the reach resulting in a constriction point in the creek.

Sub-reach 25

There is a weir located close to the start of an anabranch (Beavers Creek) that branches out from the Murrumbidgee River at about 5km downstream along the reach. Two bridges along Mundowy Lane are located on Murrumbidgee River and Beavers Creek Anabranch. Another bridge along Central Island Road cross Old Man creek at the lower section of this reach. The weir on the Beavers Creek Anabranch allows control of flows into the Beavers Creek / Old Man Creek Anabranch system under regulated conditions in Summer.

b. Historic changes based on the historical imagery

There are some observable changes in channel position between the 1967-68 black and white aerial photographs and the 2021 Maxar satellite imagery.

Sub-reach 24: Overall, extension of meanders over the years has increased the length and sinuosity of the channels.

Sub-reach 25: Overall, the extension of point bars over the years has increased the length and sinuosity of the channels. Four semi-recent meander cut-offs are noted in the reach.

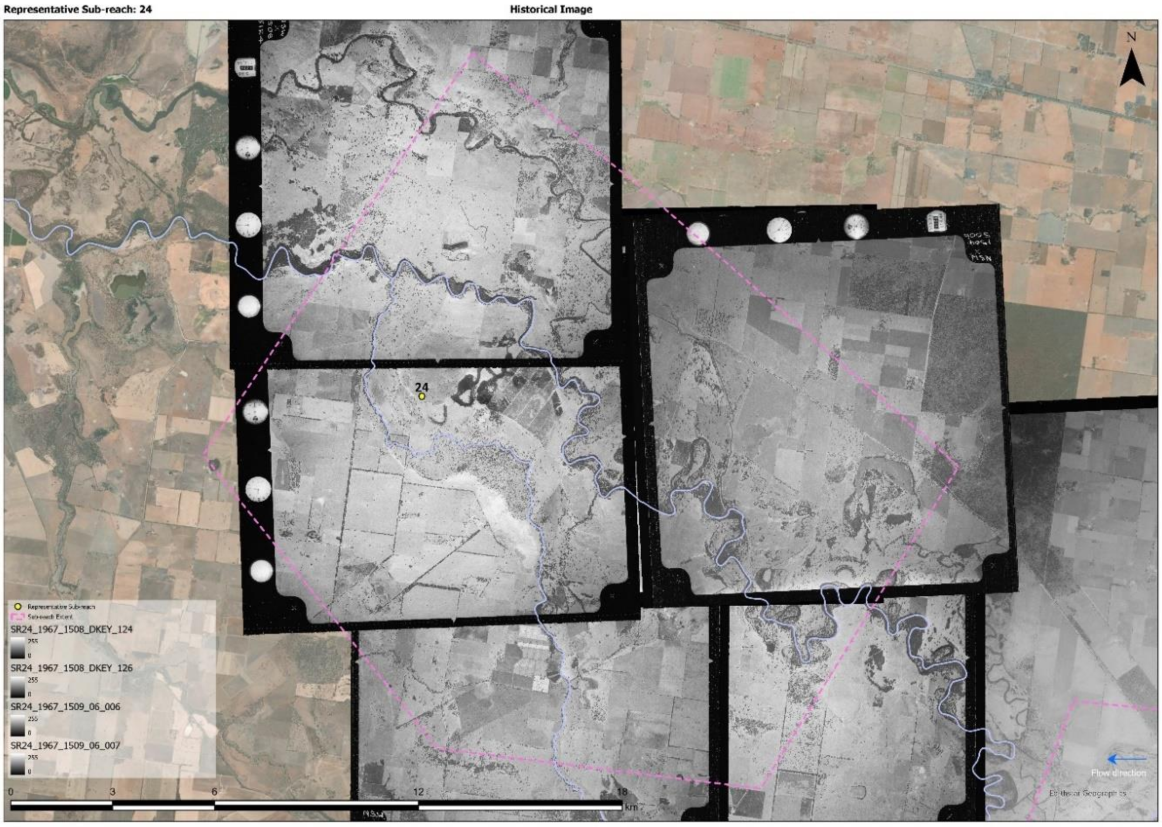

Figure 3 Historic imagery (circa 19xx) of the sub-reach extent (sub-reach 24)

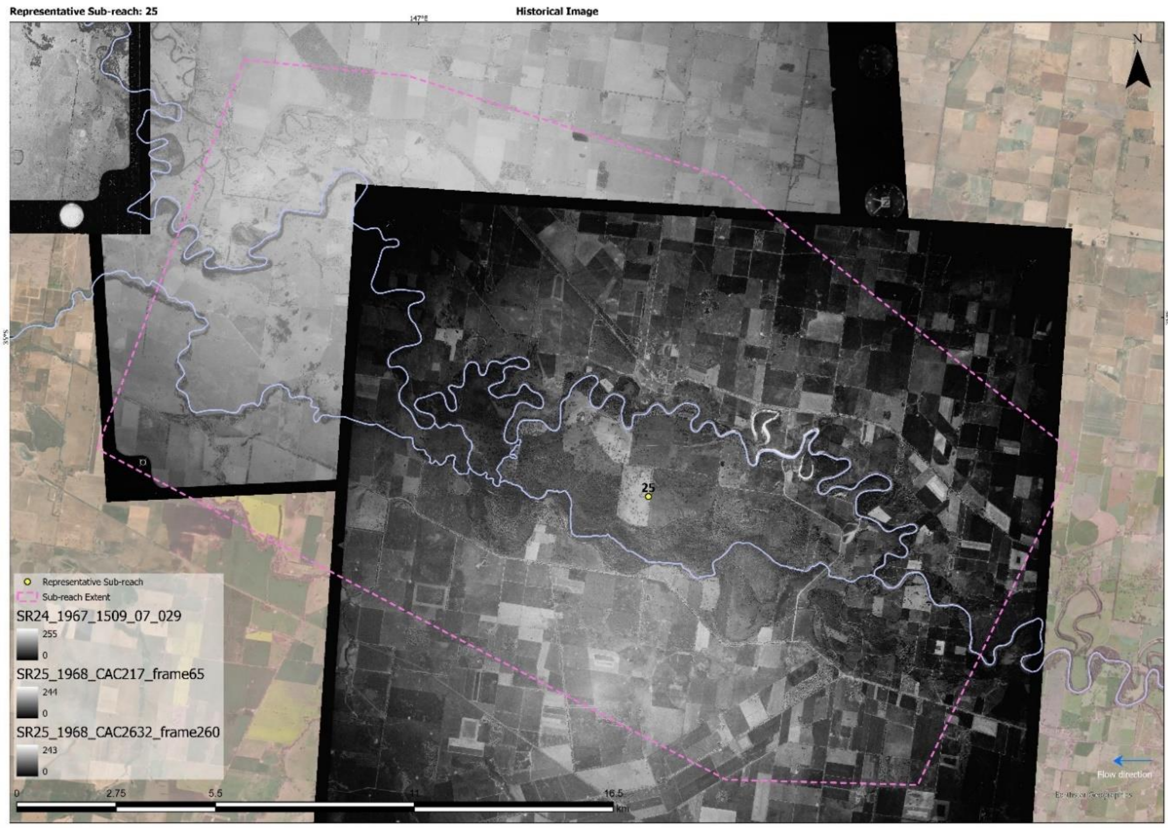

Figure 4 Historic imagery (circa 19xx) of the sub-reach extent (sub-reach 25)

c. Forms (mainly based on LiDAR)

Sub-reach 24: The LiDAR shows evidence of lateral movement of the main channel and the anabranches. The main channel and the anabranches are well-defined but not incised. Natural levee features are evident in numerous sections of the Murrumbidgee River and Old Man Creek anabranch. Artificial levee features are evident on the straightened sections of Bundidgerry Creek anabranch

Sub-reach 25: The LiDAR shows evidence of lateral movement of the main channel and the anabranches. The main channel and the anabranches are well-defined but not incised. Natural levee features are evident in numerous sections of the reach.

Anecdotal information (e.g. https://www.abc.net.au/news/rural/2014-09-03/new-riverina-weir-doubles-flow-capacity/5715308) suggests river bank erosion is occurring along this reach including the anabranch system however no monitoring data was available for this assessment.

d. Processes

Sub-reach 24: Both Bundidgerry Creek anabranch and Old Man Creek anabranch system are significantly straighter, steeper and hence shorter than the adjacent section of the Murrumbidgee River. As such, they threaten to capture flow away from the Murrumbidgee River. The creek is well developed and carries flow during both high and low regulated flow conditions. Berembed weir acts as a control for this occurring by Bundidgerry Creek.

Sub-reach 25: The key channel process occurring in this reach is one of meander cut-off through lateral migration. It is not clear if channel length is being maintained by meander extension. The outer banks are eroding on some meander bends however it is also of note that most outer bends are far less densely vegetated than their corresponding point bars.

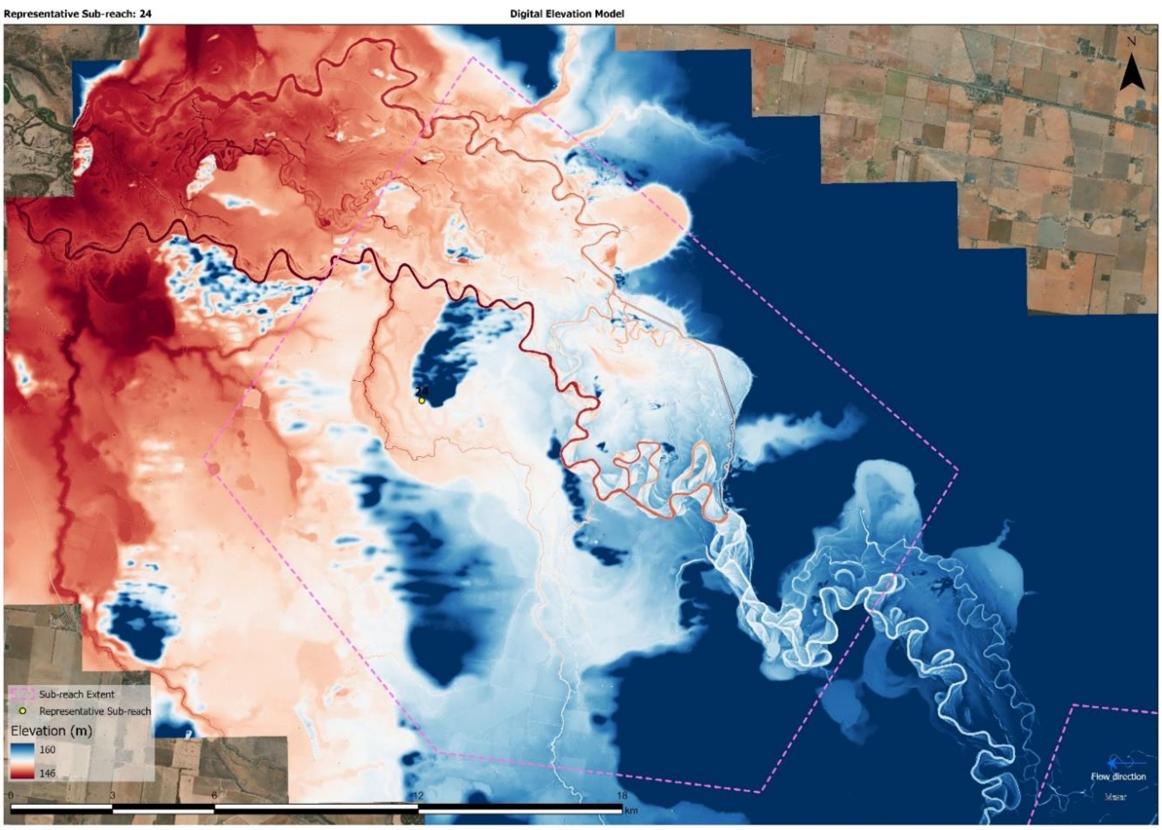

Figure 5 Lidar imagery of the sub-reach showing the different geomorphic features present (sub-reach 24)

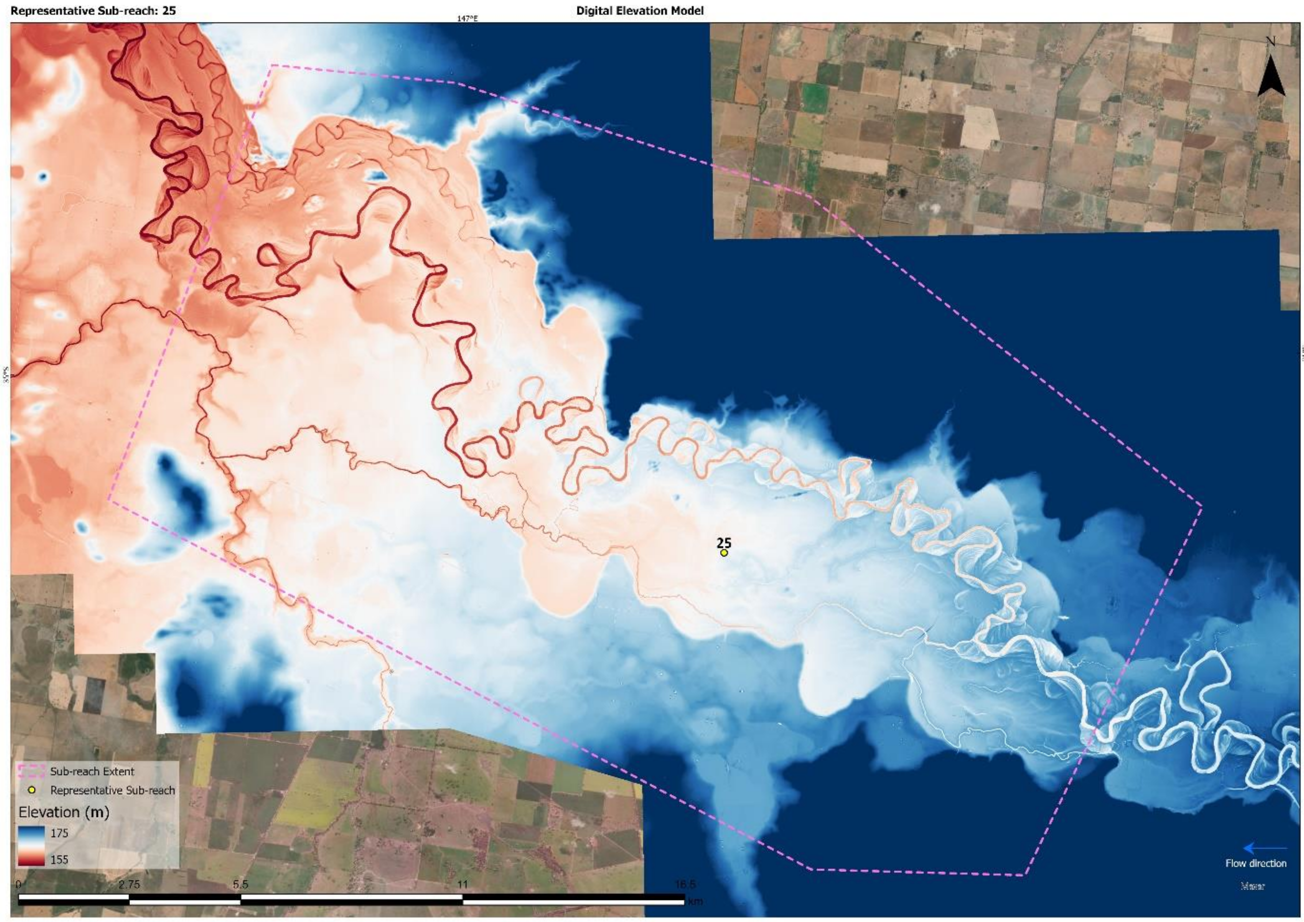

Figure 6 Lidar imagery of the sub-reach showing the different geomorphic features present (sub-reach 25)

3. Floodplain form and process

a. Anthropogenic changes

The 1968 historical imagery shows extensive agricultural land use on the floodplains, indicating previous extensive clearing of native vegetation. Removal of floodplain vegetation will have implications for overbank flow velocities and anabranch development.

b. Hydrological connections

In sub-reach 24 the Murrumbidgee River and Old Man Creek Anabranch do not appear to be incised, suggesting that the floodplain is hydrologically well-connected. Flows are distributed unproportionally across the main channel and the anabranches with varying flows. This is further affected by Berembed weir

In sub-reach 25 the channel does not appear to be incised, suggesting that the floodplain is hydrologically well-connected. Flows are distributed unproportionally across the main channel and the anabranches with varying flows.

Bankfull capacity is around 16,000 ML/d based on the available inundation mapping.

Inundation mapping for sub-reach 24, Old Man Creek experiences more extensive floodplain inundation up to 44,000 ML/d than the main Murrumbidgee River channel although the area of floodplain is tightly constrained to a corridor along the channel, possibly due to the presence of levees. Extensive floodplain inundation occurs for flows above 48,000 ML/d.

Inundation mapping shows that in sub-reach 25 (upstream sub-reach), Beavers Creek is more hydraulically connected to the floodplain than the Murrumbidgee River channel with extensive inundation through the Berry Jerry National Park for flows from 16,000 ML/d to 44,000 ML/d. There is minor floodplain inundation adjacent to the main river channel through this sub-reach. Extensive floodplain inundation occurs for flows above 48,000 ML/d.

c. Form (mainly based on LiDAR)

The LiDAR data and aerial imagery for both sub-reaches shows a complex topographic floodplain surface, comprising contemporary and relict meanders, ox-bow lakes, flood runners, paleochannels, scroll bars and anabranches.

d. Processes

In both sub-reaches, paleochannels and flood runners are activated by high flows. Anabranches in this reach are established with new anabranches developing. The development and evolution of anabranches involves the erosion and enlargement of a channel system until most, if not all of the flow has been captured from the parent channel.

The Beaver Creek anabranch system is significantly straighter, steeper, and hence shorter than the adjacent section of the Murrumbidgee River. The creek is well developed and carries flow during both high and low regulated flow conditions. However, this anabranch is regulated by a weir and flood gates at its upstream end. A crossing/weir at the downstream end also prevents flow from re-entering the Murrumbidgee and forces flows much farther downstream.

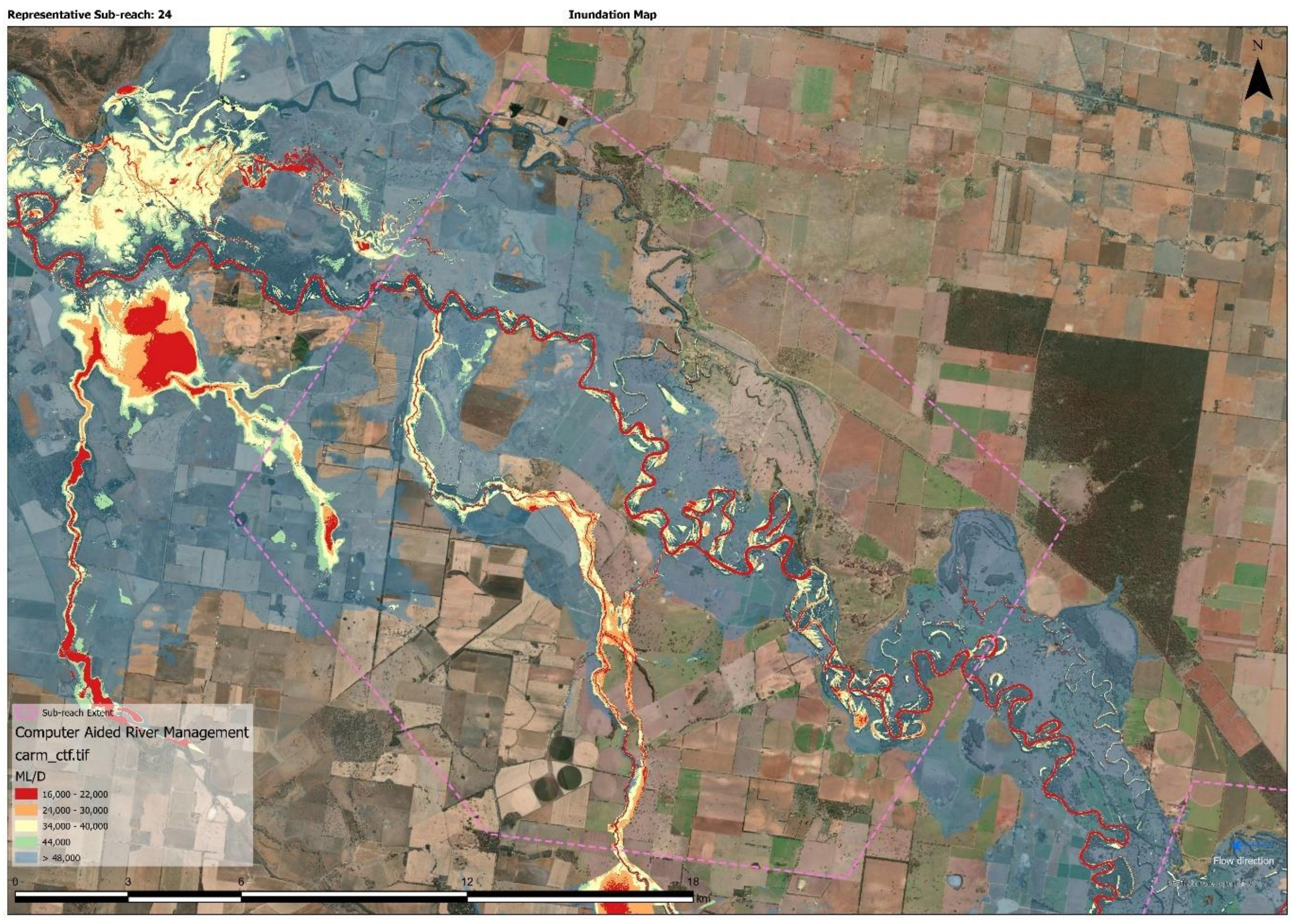

Figure 7 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs) (sub-reach 24)

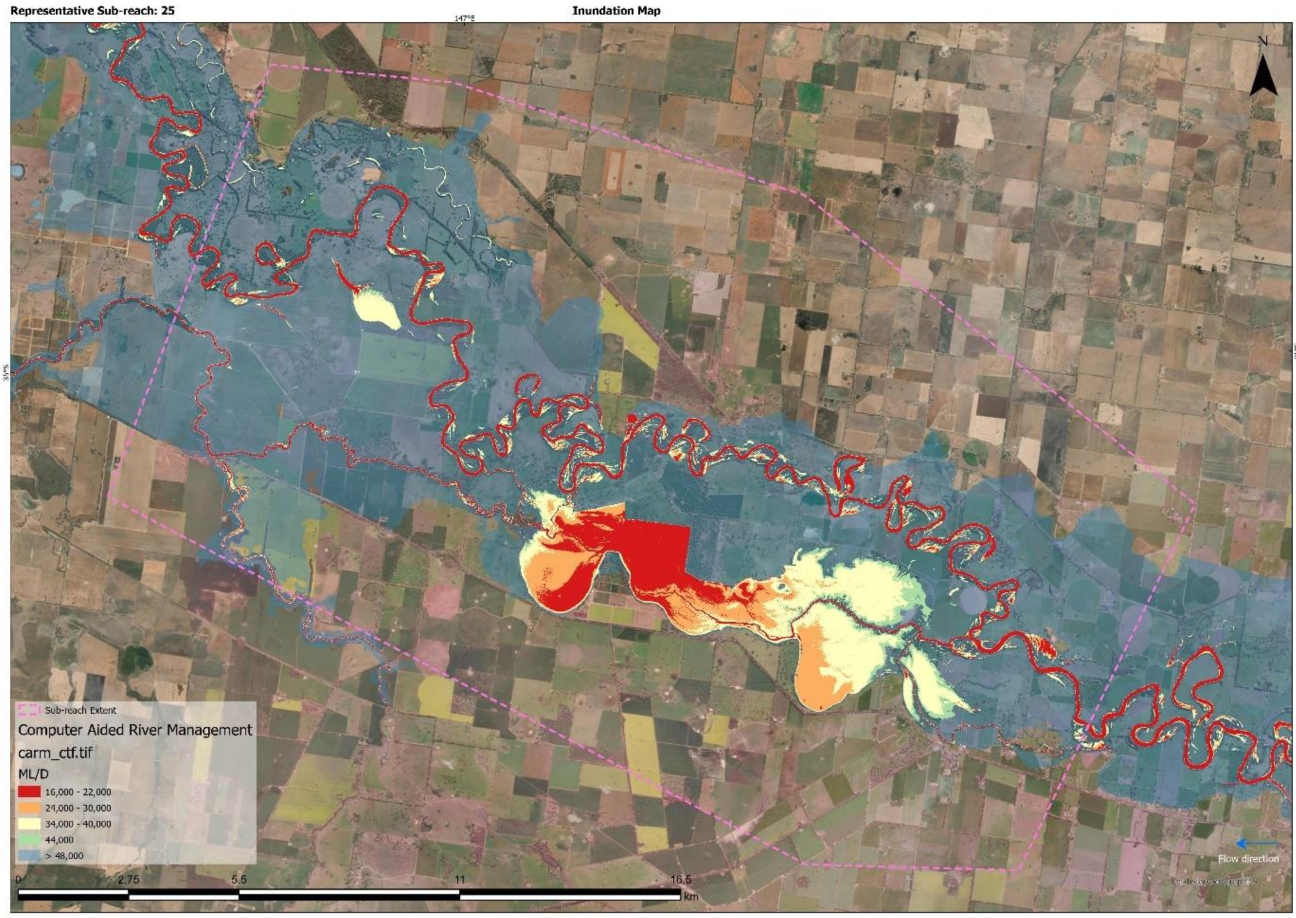

Figure 8 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs) (sub-reach 25)

4. Base case

The base case geomorphic features and processes are summarised in Table 1 and Table 2.

Table 1   Geomorphic features and processes, sub-reach 24

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (levee)	Deposition
Floodplain (cutoffs)	Avulsion / meander migration / meander extension
Floodplain (sub-bankfull - anabranch/floodrunners	Avulsion
Floodplain (> bankfull – anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Table 2   Geomorphic features and processes, sub-reach 24

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (levee)	Deposition
Channel (bars)	Deposition
Floodplain (cutoffs)	Avulsion / meander migration / meander extension
Floodplain (sub-bankfull - anabranch/floodrunners	Avulsion
Floodplain (> bankfull – anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 24 & 25 are summarised in Table 4 and Table 5. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to these reaches are as follows.

Table 3 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 4 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios (24)

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Cutoffs	Meander migration	1	2	3	3	3
Levees	Desposition	0	0	2	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.73**	**0.52**	**0.48**	**0.00**
Likelihood (W40 events per year)		1.00	0.73	0.61	0.59	0.00
Likelihood (W32 events per year)		1.00	0.73	0.54	0.50	0.00

Table 5 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios (25)

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Bars	Deposition	2	3	3	1	1
Cutoffs	Meander migration	1	2	3	3	3
Levees	Desposition	0	0	2	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.73**	**0.52**	**0.48**	**0.00**
Likelihood (W40 events per year)		1.00	0.73	0.61	0.59	0.00
Likelihood (W32 events per year)		1.00	0.73	0.54	0.50	0.00

The current trajectory of both sub-reaches (channel and floodplain) in terms of physical form is likely to be ongoing river processes of lateral migration, meander extension and meander cut-off. No meanders appear to be at a stage at present where another cut-off would be imminent. The lateral migration of this channel and the anabranches of Beavers Creek and Old Man Creek appear to be very slow.

The base case for sub-reach 24 includes the geomorphic processes of meander extension, cut-offs, and ongoing development of the anabranch. The base case for sub-reach 25 is similar with lateral migration (bank erosion), meander extension and meander cut-offs as the main processes occurring. Bank erosion can also be enhanced in locations where there is a rapid change in flow such as upstream and downstream of weirs or regulating structures.

Under the flow options scenarios change in the flow regime may increase the rate of change of these processes although the changes are not expected to be significantly above current rates of change.

Table 6 Geomorphic impact score under current constraints and for the flow options scenarios (24)

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbanks	5.5	5.6	3%	5.5	1%
Cutoffs	5.5	6.0	10%	5.6	2%
Levees	2.5	3.0	17%	2.6	4%
Anabranches / Floodrunners (sub-bankfull)	4.5	5.0	11%	4.6	3%
Floodplain (> bankfull)	1.4	1.8	18%	1.5	3%
Anabranches / Floodrunners (> bankfull)	1.4	1.8	18%	1.5	3%
Average	**3.5**	**3.9**	**12%**	**3.5**	**2%**

Table 7 Geomorphic impact score under current constraints and for the flow options scenarios (25)

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbanks	5.5	5.6	3%	5.5	1%
Bars	6.2	6.6	5%	6.3	1%
Cutoffs	5.5	6.0	10%	5.6	2%
Levees	2.5	3.0	17%	2.6	4%
Anabranches / Floodrunners (sub-bankfull)	4.5	5.0	11%	4.6	3%
Floodplain (> bankfull)	1.4	1.8	18%	1.5	3%
Anabranches / Floodrunners (> bankfull)	1.4	1.8	18%	1.5	3%
Average	**3.9**	**4.3**	**11%**	**3.9**	**2%**

6. Limitations and Constraints

This desktop assessment is based on limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

DPIE. (2020). *Murrumbidgee Long Term Water Plan Part A: Murrumbidgee catchment.* Report by the NSW Department of Planning, Industry and Environment, July 2020.

Olive, L.J. and Olley, J.M. (1997). River regulation and sediment transport in a semiarid river: the Murrumbidgee River, New South Wales, Australia, Human Impacts on Erosion and Sedimentation, Proceedings of Rabat Symposium S6, IAHS Publication No. 245

Owens, J.W. (1998). Late quaternary evolution of fluvial and aeolian sediments in the upper Murrumbidgee valley (unpublished MAppSc dissertation), Wagga Wagga, Australia, Charles Sturt University, 242p

Page, K.J. and Nanson, G.C., 1996. Stratigraphic architecture resulting from Late Quaternary evolution of the Riverine Plain, south-eastern Australia. Sedimentology, 43(6), pp.927-945.Sinclair Knight Merz (2011). Environmental Water Delivery: Murrumbidgee Valley. Prepared for Commonwealth Environmental Water, Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Sub-Reach 26 Geomorphic Outline – Wagga Wagga Reach

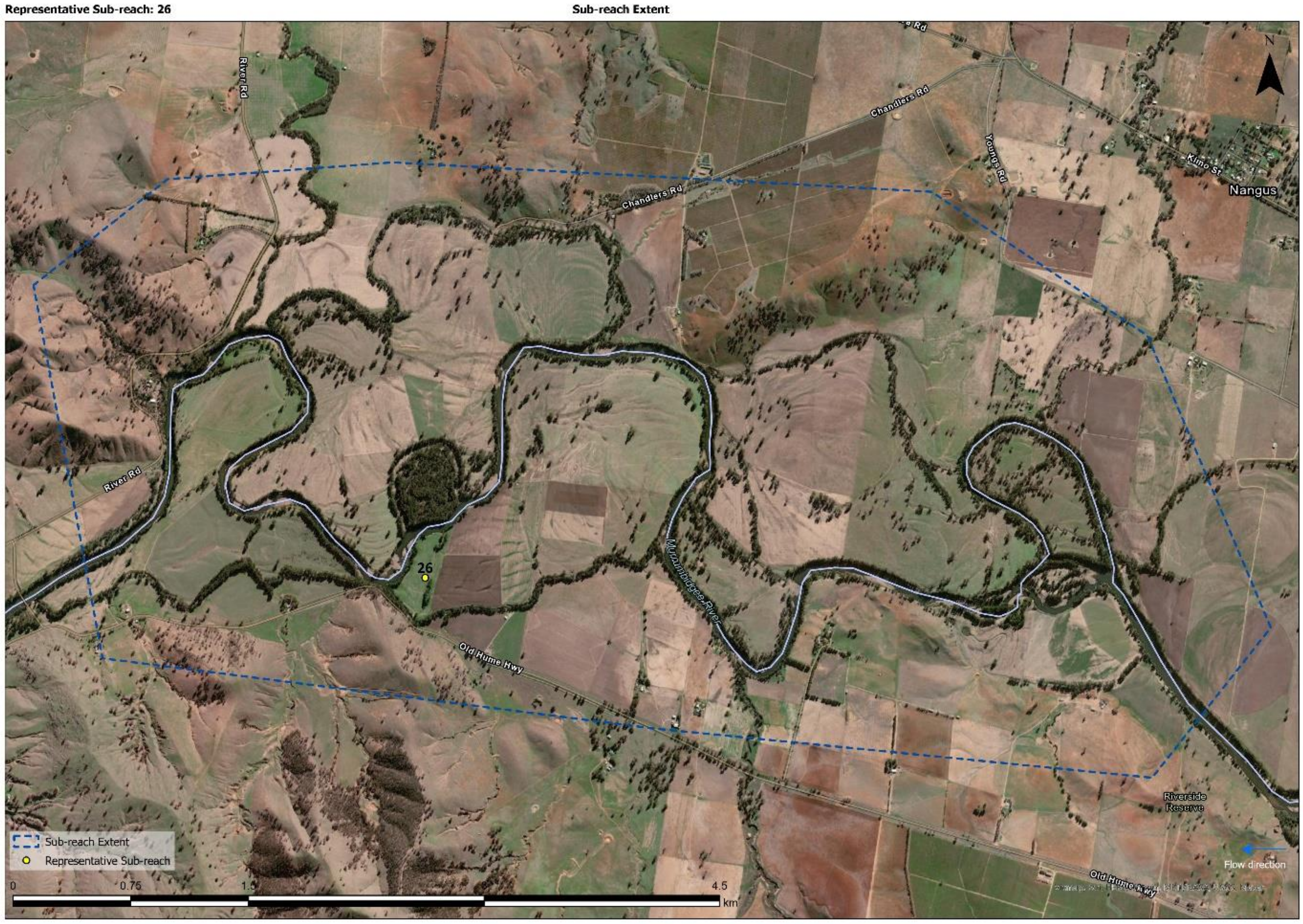

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The site is located on the Murrumbidgee River approximately 24 km downstream of the town of Gundagai. The reach length is approximately 16 km. The reach is dominated by an extensive floodplain extending between 1.5 to 2.5 km wide and bounded by isolated outcrops.

2. Channel form and processes

a. Anthropogenic Influences

Water storage infrastructure upstream of the reach will have had the most significant impact on the reach through changes to sediment budget along with flow seasonality, variability and duration. Tanangara Reservoir and Burrinjuck Dam are located upstream of site. Other water storages on the tributaries upstream include Happy Jacks Dam, Tumut Pond Dam, Tumut Two Dam, Talbingo Dam, Jounama Dam, and Blowering Dam, Corin Dam, Bindura Dam and Cotter Dam.

b. Historic changes based on the historical imagery

There are some observable changes in channel position between the 1969 black and white aerial photographs and the 2021 Maxar satellite imagery. Overall, the extension of point bars over the years has increased the length and sinuosity of the channels. Two semi-recent avulsions are noted in the reach.

c. Forms (mainly based on LiDAR)

The LiDAR shows evidence of lateral movement of the main channel and the anabranches. The main channel banks are fairly steep with height over 5-7m. Natural levee features are evident in numerous sections of the reach.

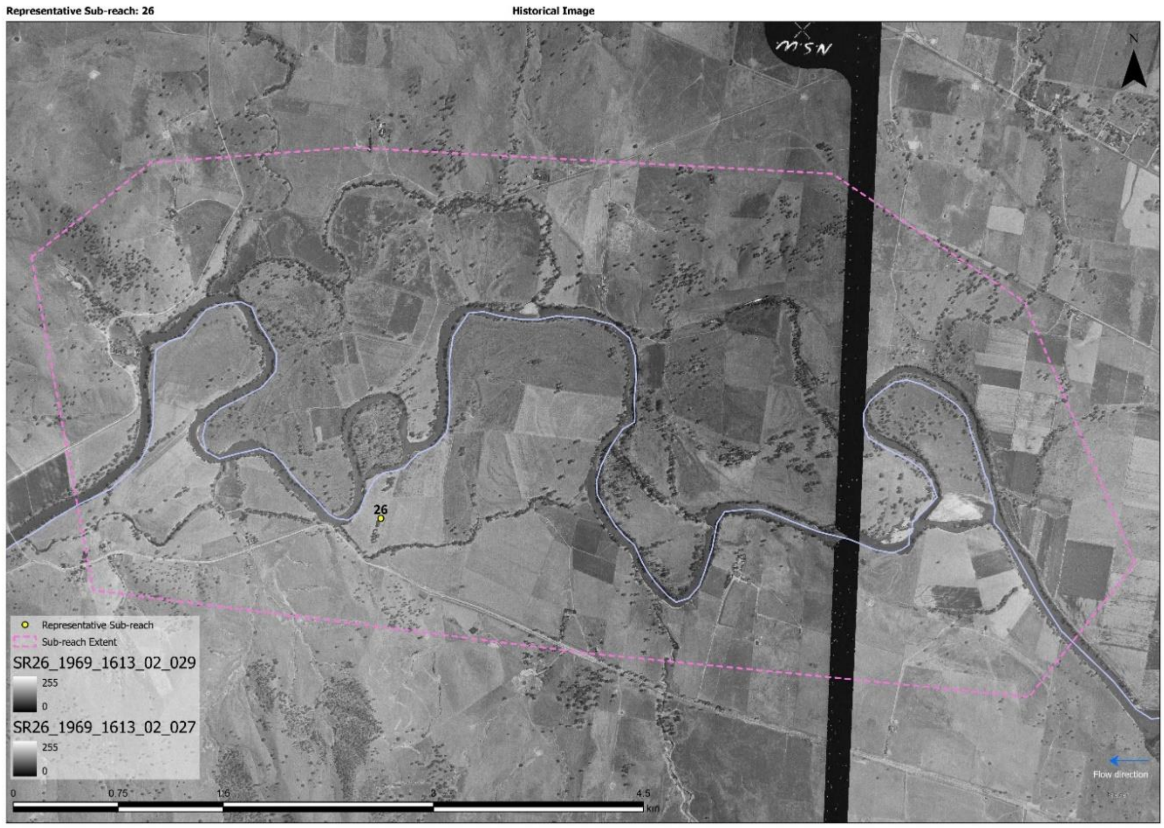

Figure 2 Historic imagery (circa 19xx) of the sub-reach extent

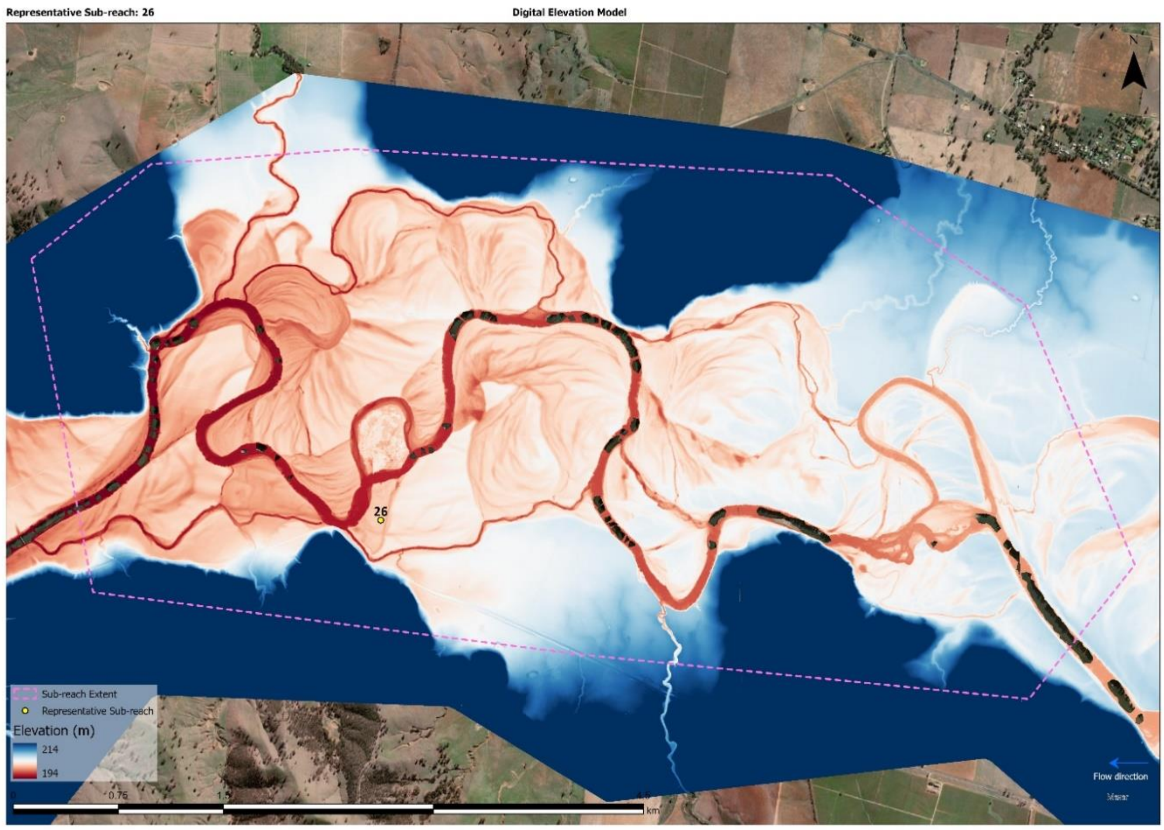

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

d. Processes

Two semi-recent avulsions are noted in the reach. The avulsions are located at approximately 1 km and 10 km from the upstream extent of the reach which has short-circuited a long meander bend. The short-circuited main channel upstream is still flowing and not cut-off. In contrast the downstream avulsion has resulted in a cut-off that has likely infilled and is only activated during high flows. The extension of meander bends is noted with the extension of point bars and the erosion of the outside of meander bends.

3. Floodplain form and process

a. Anthropogenic changes

The 1969 historical imagery shows extensive agricultural land use on the floodplains, indicating previous extensive clearing of native vegetation. Removal of floodplain vegetation will have implications for overbank flow velocities and anabranch development.

b. Hydrological connections

The channel does not appear to be incised, suggesting that the floodplain is hydrologically well-connected. Flows are distributed unproportionally across the main channel and the anabranches with varying flows.

Inundation mapping indicates the bankfull capacity is > 16,000 ML/d and the flows remain predominantly in channel up to around 44,000 ML/d. Extensive floodplain inundation is shown for flows above 48,000 ML/d.

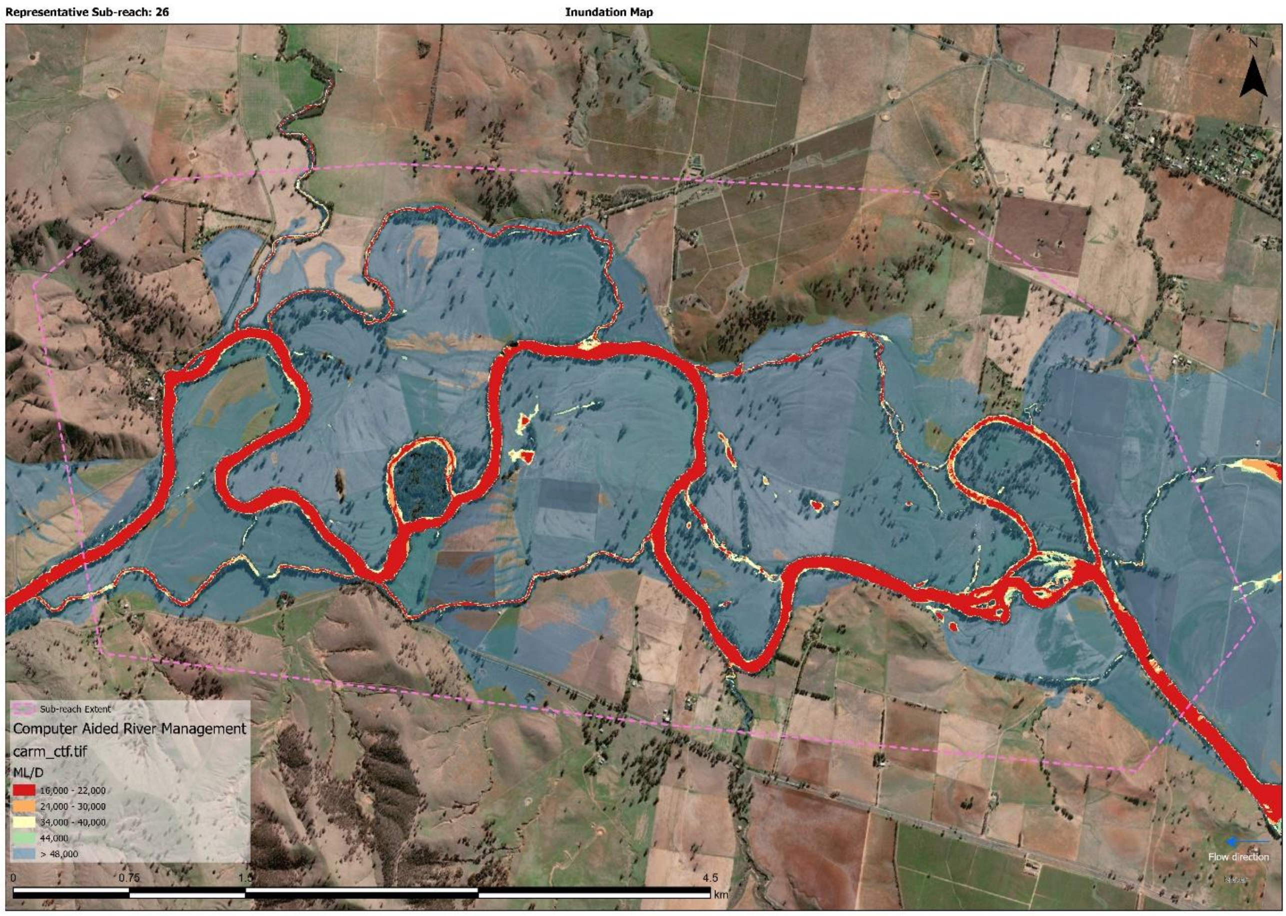

Figure 4 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

c. Form (mainly based on LiDAR)

The flat and wide valley floor has numerous geomorphic features including contemporary and relict meanders, flood runners and anabranching channels. The LiDAR data shows the extensive network of palaeochannels as a result of lateral movement of the channels.

d. Processes

Infrequent inundation and low sediment yields mean that rates of change are low. Flood runners are activated by high flows. Anabranches in this reach are established with new anabranches developing. The development and evolution of anabranches involves the erosion and enlargement of a channel system until most, if not all of the flow has been captured from the parent channel.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic features and processes, sub-reach 26

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (bars)	Deposition
Channel (levee)	Deposition
Floodplain (cutoffs)	Avulsion / meander migration / meander extension
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (>bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 26 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to these reaches are as follows.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios

Geomorphic Feature and Process		Flow Associations Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Bars	Deposition	1	2	3	3	3
Cutoffs	Avulsion / meander migration-	1	2	3	3	3
Levees	Desposition	0	0	2	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.53**	**0.13**	**0.11**	**0.00**
Likelihood (W40 events per year)		1.00	0.62	0.12	0.11	0.00
Likelihood (W32 events per year)		1.00	0.61	0.12	0.10	0.00

The base case trajectory of the reach (channel and floodplain) is likely to be ongoing river processes of lateral migration (bank erosion), meander extension and meander cut-off. Another cut-off is likely to occur in the future as the river continue to attempt to short-circuit the main channel. The lateral migration of this channel appears to be very slow. Under the flow options scenarios change in the flow regime may increase the rate of change of these processes although the changes are not expected to be significantly above current rates of change.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario Current Constraints	W40	% change	W32	% change
Riverbanks	4.3	4.5	4%	4.4	4%
Bars	2.8	2.9	5%	2.9	4%
Cutoffs	2.8	2.9	5%	2.9	4%
Levees	0.6	0.6	-3%	0.5	-7%
Anabranches / Floodrunners (sub-bankfull)	1.8	1.9	8%	1.9	7%
Floodplain (> bankfull)	0.3	0.3	0%	0.3	-7%
Anabranches / Floodrunners (> bankfull)	0.3	0.3	0%	0.3	-7%
Average	**1.8**	**1.9**	**5%**	**1.9**	**3%**

6. Limitations and Constraints

This desktop assessment is based on limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Olive, L.J. and Olley, J.M. (1997). River regulation and sediment transport in a semiarid river: the Murrumbidgee River, New South Wales, Australia, Human Impacts on Erosion and Sedimentation, Proceedings of Rabat Symposium S6, IAHS Publication No. 245

Owens, J.W. (1998). Late quaternary evolution of fluvial and aeolian sediments in the upper Murrumbidgee valley (unpublished MAppSc dissertation), Wagga Wagga, Australia, Charles Sturt University, 242p

Page, K.J. and Nanson, G.C., 1996. Stratigraphic architecture resulting from Late Quaternary evolution of the Riverine Plain, south-eastern Australia. Sedimentology, 43(6), pp.927-945.Sinclair Knight Merz (2011). Environmental Water Delivery: Murrumbidgee Valley. Prepared for Commonwealth Environmental Water, Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Sinclair Knight Merz (2011). *Environmental Water Delivery: Murrumbidgee Valley.* Prepared for Commonwealth Environmental Water, Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Example Sub-Reach 27 & 29 Geomorphic Outline – Gundagai Reach

Figure 1 Sub-reach 27 map extent

Figure 2 Sub-reach 29 map extent

1. Sub-reach position in catchment and general description

These sub-reaches are on the Murrumbidgee River and includes the confluence with the Tumut River. The reach length is approximately 18 km in length. The reach starts at a large compound meander bend. The river course in this reach is controlled by alternating ridge outcrops that are orientated in a North-South direction. From the aerial photography the river in this reach appears to be straightening with several meander bends exhibiting signs of erosion along flood runners, short-circuiting meander bends.

2. Channel form and processes

a. Anthropogenic changes

Water storage infrastructure upstream of the reach will have had the most significant impact on the reach through changes to sediment budget along with flow seasonality, variability and duration. Tanangara Reservoir and Burrinjuck Dam are located upstream of site. Other water storages on the tributaries upstream include Happy Jacks Dam, Tumut Pond Dam, Tumut Two Dam, Talbingo Dam, Jounama Dam, and Blowering Dam, Corin Dam, Bindura Dam and Cotter Dam.

b. Historic changes based on the historical imagery

There were few observable changes in channel position between the 1958 black and white aerial photograph and the 2021 Maxar satellite imagery. Overall, there has been reconfiguration of the point bars along the river and at the confluence with Tumut River. The flood chute located approximately 6.5km downstream of the confluence is observable in the 1958 imagery. Sand mining activity was not present in the 1986 historical photograph. The 2021 imagery (likely with a relatively lower water level) is showing a more sinuous low flow channel due to the presence of sand sluglettes (Rutherfurd, 1996) in the main channel.

c. Forms (mainly based on LiDAR)

The LiDAR shows evidence of lateral movement of the main channel. The channel width reduces from 80m wide (before the large compound meander) to 50m wide (along the large upstream compound meander) with indications of channel incision as the channel is narrowed. The banks of the outside bend are very steep with height over 10m and approximately a 1:1 slope.

The channel is geologically controlled and is meandering around the alternating ridge lines. In channel features include attached bars and benches, a majority of bars are exposed indicating highly mobile bed sediments and frequent reconfiguration of the in-channel features. Whereas some pools are evident, excess sediment is also indicated by the observed sand sluglettes which are evident, particularly within this reach.

d. Processes

There are several potential avulsion paths along the downstream portion of this reach. It is evident that the river adopts a straight and shorter course during high flow events through flood runners. This indicated by long areas of exposed sandy material located along the flood runners, which short-circuit meander bends. The degree of topographic change is not evident from the aerial photography. It is likely that portions of these features are depositional (sand splays: sand deposited on the inset floodplain during over bank events). However, various scour pools are evident along these paths and it is clear that the avulsion process has been initiated in some areas.

A vegetated anabranch located just before the start of the large compound meander bend is activated during higher flows, resulting in a short and straighter flow course compared to the main channel. Sand sluglettes are observed in various locations along the reach, increasing the sinuosity of the low flow channel. Some of these sand slugs are partly vegetated.

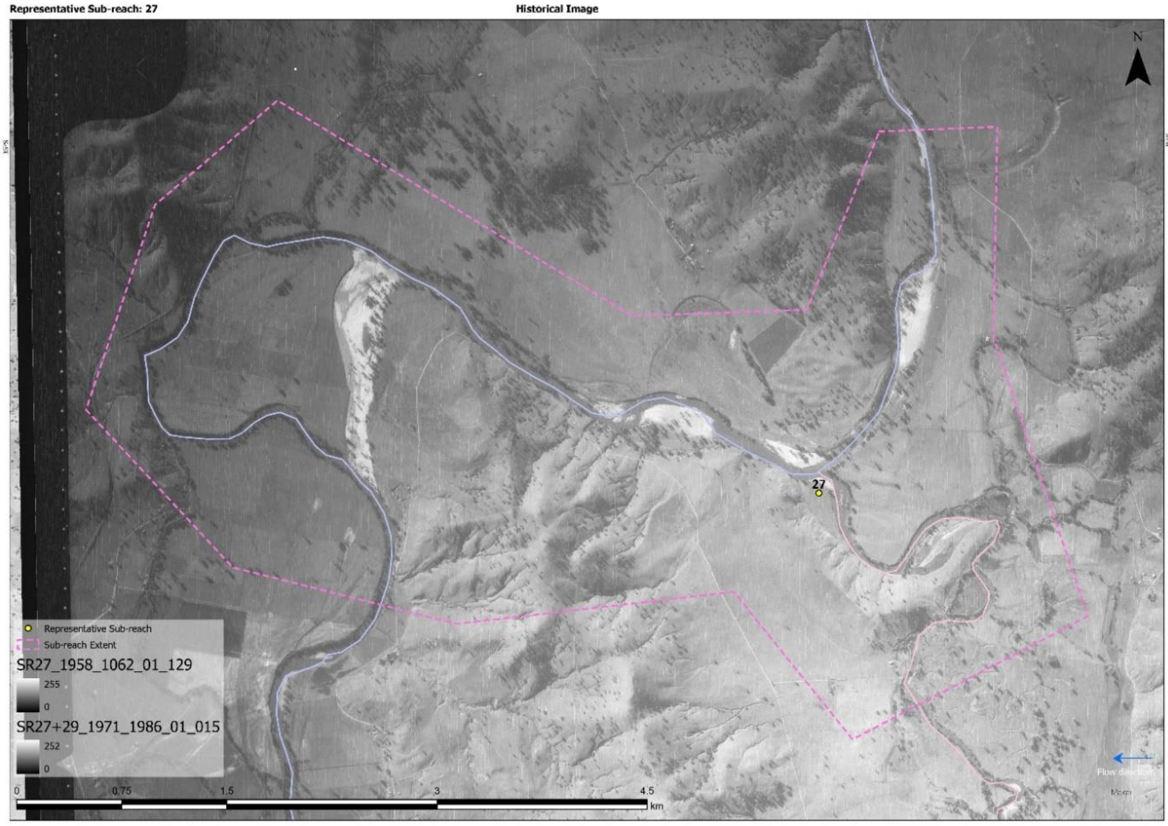

Figure 3 Historic imagery (circa 1945) of the sub-reach 27 extent

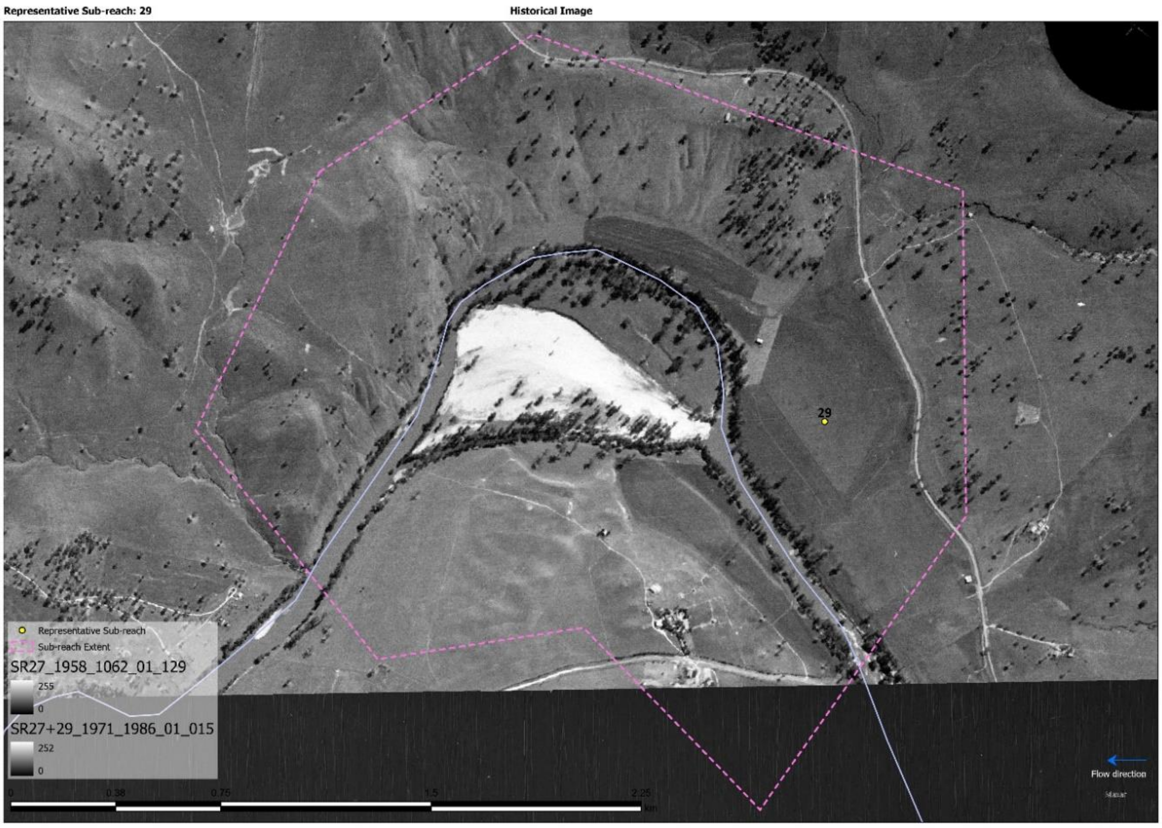

Figure 4 Historic imagery (circa 1945) of the sub-reach 29 extent

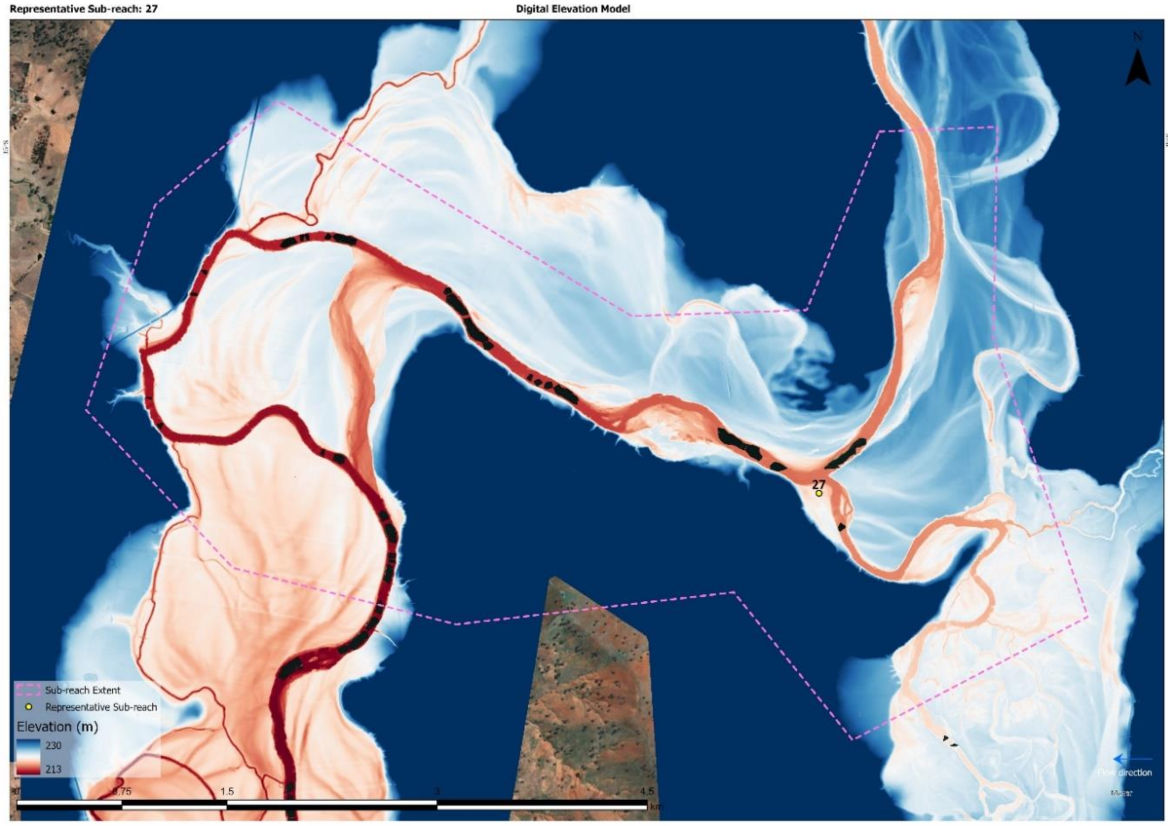

Figure 5 Lidar imagery of the sub-reach 27 showing the different geomorphic features present

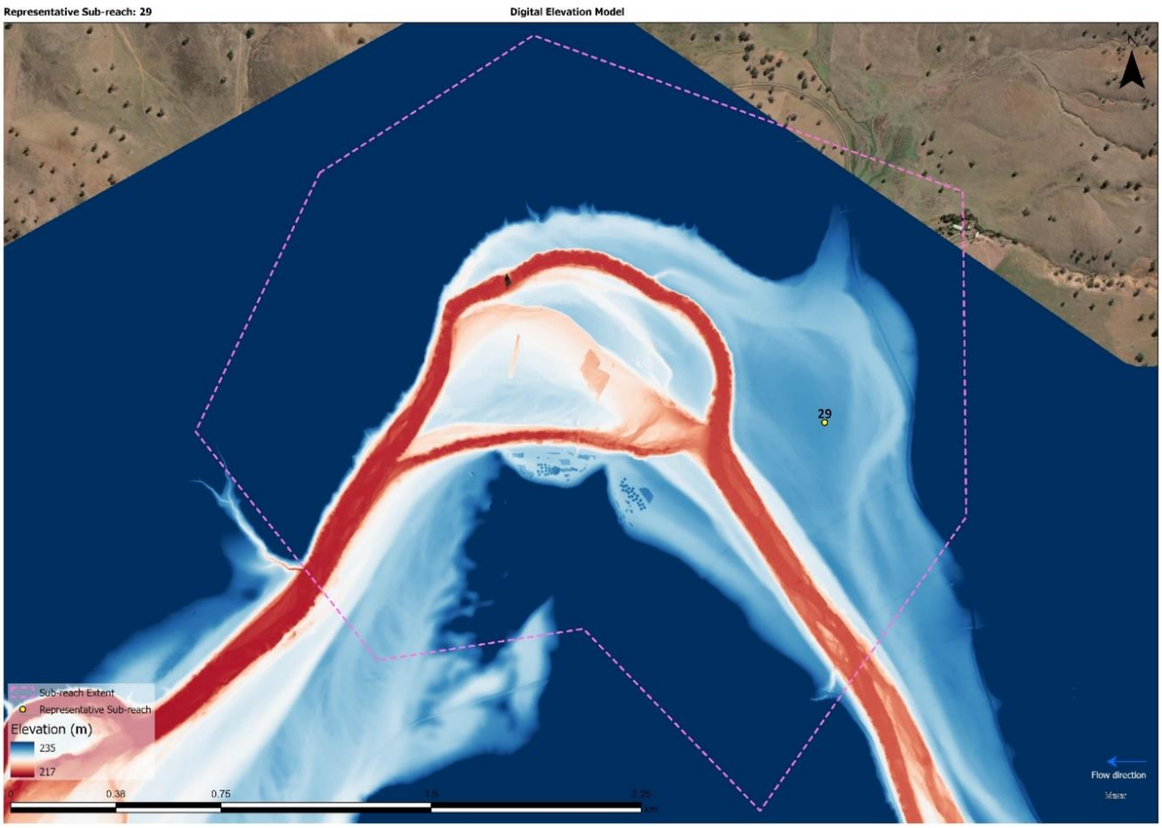

Figure 6 Lidar imagery of the sub-reach 29 showing the different geomorphic features present

3. Floodplain form and process

e. Anthropogenic changes

The historical imagery shows extensive agricultural land use on the floodplains, indicating previous extensive clearing of native vegetation. A few buildings and roads/tracks that are evident on the left bank downstream of the confluence were previously not therein the historical imagery.

Sand mining is also evident in the area from aerial photography. This is being undertaken on the adjacent floodplain and, in one case, within a flood runner. It is not clear from the aerial photography whether the mining within the flood runner is into a sand splay (sand deposited on the inset floodplain during over bank events) or into the inset floodplain itself. Regardless, such activities are high risk in terms of triggering geomorphic change (i.e., forming an avulsion) and should be discouraged.

f. Hydrological connections

There is a small ephemeral creek located at approximately 13.5km along the reach that joins the main channel but is unlikely to contribute to significant changes to form and processes of the channels or floodplain. An anabranch located at approximately 15.5km along the reach is likely to be activated during higher flow condition and carry some of the inflows along for 10km before re-joining the main river.

The floodplain is hydrologically well-connected. Flows are distributed disproportionally across the main channel and the anabranches with varying flows.

Inundation mapping for sub-reach 27 shows the flows are predominantly confined to the main channel up to 40,000 ML/d except for the potential anabranch (shown through the avulsion path across the floodplain). This flow path is engaged at flows around 30,000 ML/d.

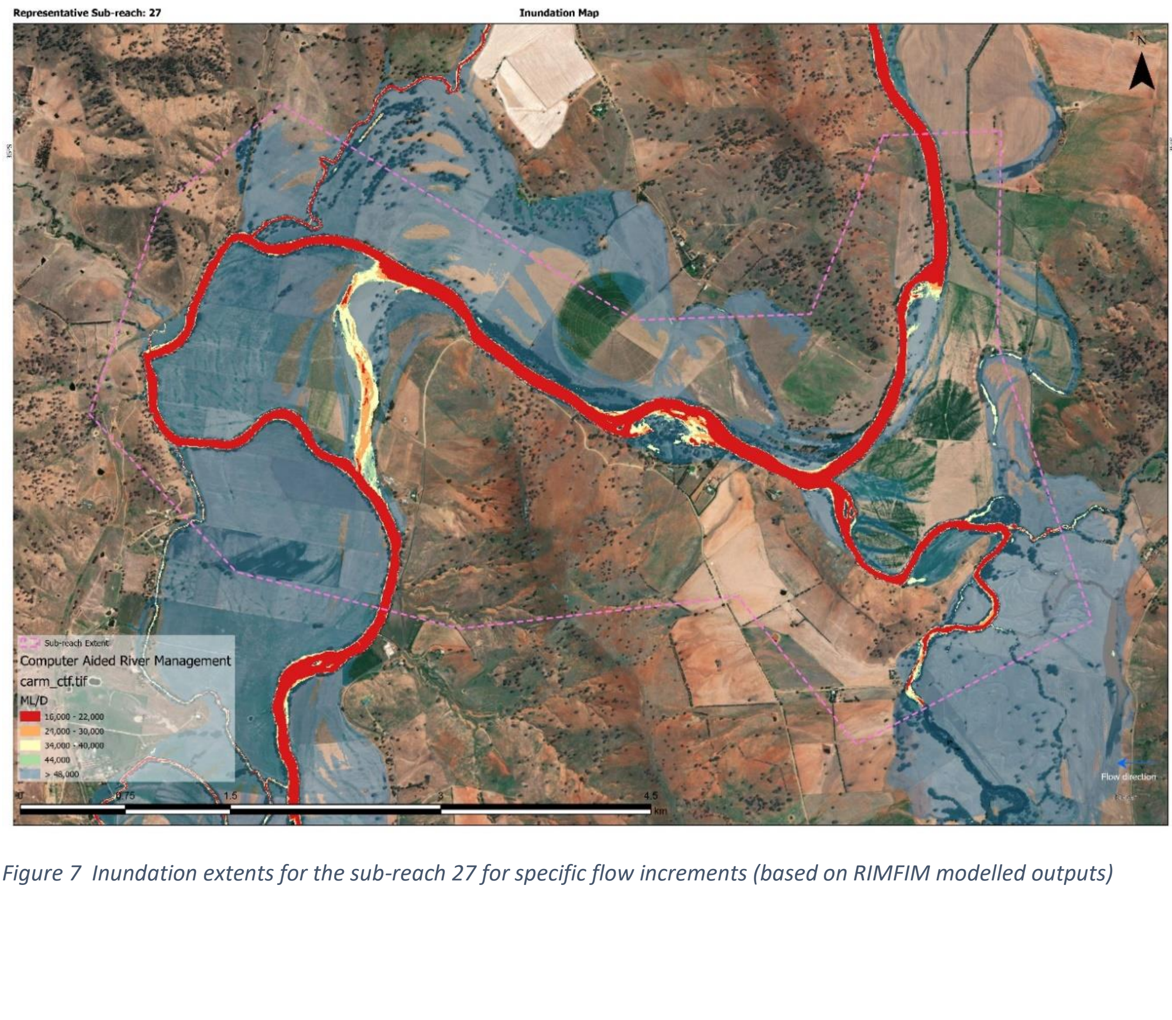

Figure 7 Inundation extents for the sub-reach 27 for specific flow increments (based on RIMFIM modelled outputs)

Inundation mapping for sub-reach 29 indicates the developing anabranch is almost hydraulically connected for flows as low as 22,000 ML/d. Flows above 22,000 ML/d connect to the new pathway and will continue to erode back to the main channel, enhancing the connection.

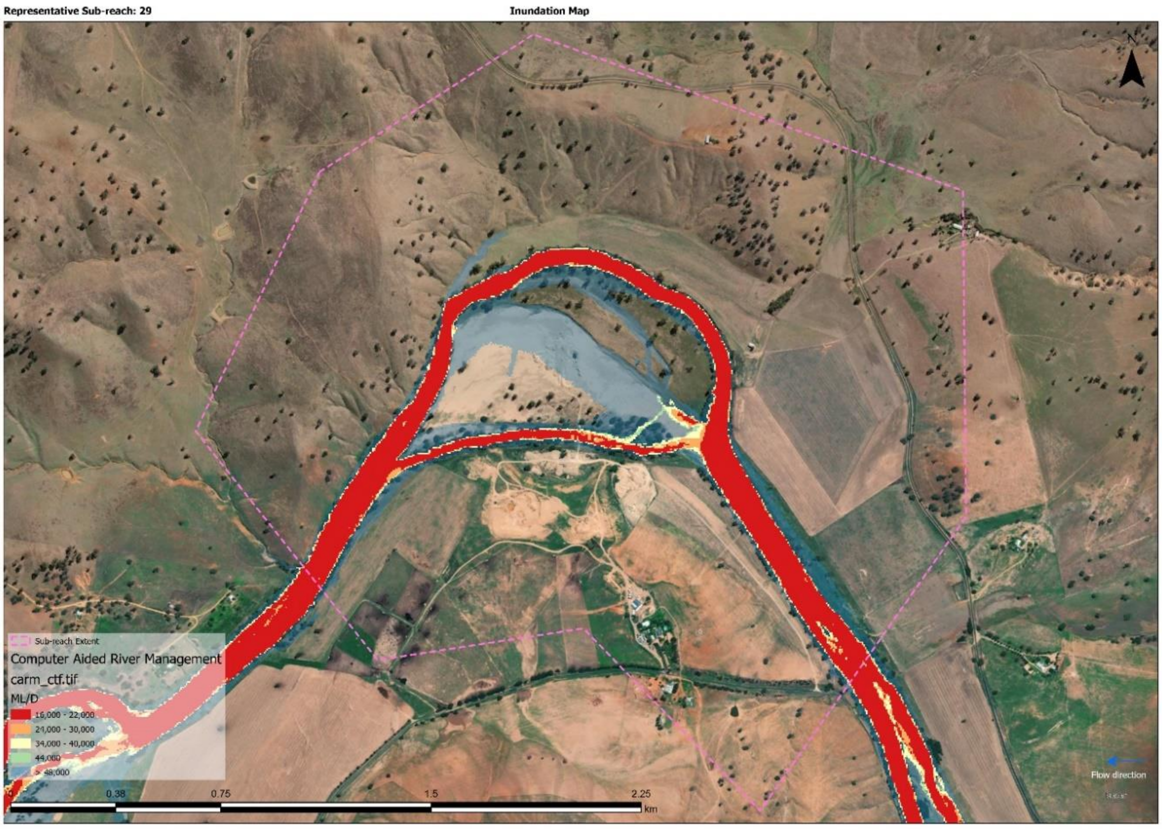

Figure 8 Inundation extents for the sub-reach 29 for specific flow increments (based on RIMFIM modelled outputs)

g. Form (mainly based on LiDAR)

The floodplains have numerous geomorphic features including contemporary and relict meanders, and cut-offs. The LiDAR data shows extensive lateral movement of the channels to the north of the current location of the confluence with Tumut River.

h. Processes

Anabranch and flood runners are activated by high flows across the flood plain.

4. Base case

The base case geomorphic features and processes are summarised in the following tables.

Table 1 Geomorphic features and processes, sub-reach 27

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (bars)	Deposition
Channel (levees)	Deposition
Floodplain (cutoffs)	Avulsion / meander migration / meander extension
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (>bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Table 2 Geomorphic features and processes, sub-reach 29

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (bars)	Deposition
Channel (benches)	Deposition
Channel (sand slugs)	Deposition
Channel (scour pools)	Erosion
Floodplain (cutoffs)	Avulsion / meander migration / meander extension
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (>bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 27 and 29 are summarised in Table 4 and Table 5. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to these reaches are as follows.

Table 3 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

Table 4 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios (27)

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Bars	Deposition	1	2	3	3	3
Cutoffs	Avulsion / meander migration	1	2	3	3	3
Levees	Desposition	0	0	2	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.53**	**0.13**	**0.11**	**0.00**
Likelihood (W40 events per year)		1.00	0.62	0.12	0.11	0.00
Likelihood (W32 events per year)		1.00	0.61	0.12	0.10	0.00

Table 5 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios (29)

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Bars	Deposition	1	2	3	3	3
Cutoffs	Avulsion / meander migration	1	2	3	3	3
Benches	Desposition	2	3	3	1	1
Sand slug	Desposition	1	2	2	2	2
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Scour pools	Erosion	1	2	3	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.53**	**0.13**	**0.11**	**0.00**
Likelihood (W40 events per year)		1.00	0.62	0.12	0.11	0.00
Likelihood (W32 events per year)		1.00	0.61	0.12	0.10	0.00

The current trajectory of the sub-reaches (channel and floodplain) is likely to be ongoing channel straightening. Channel straightening through avulsion is likely to progress episodically during high flows (e.g., flows above bankfull). This is a natural process which has likely been enhanced through vegetation clearing and sand mining.

The trajectory under base case conditions is for continued reconfiguration of the unvegetated sand bars can be expected. The sand sluglettes identified in sub-reach 29 will continue to move downstream. It is likely that the source of this sand is from the progressing avulsions. Once the avulsions occur, more sand can be expected within the channel. Increased flow velocities resulting from the channel straightening may dissipate the sluglettes during high flows, with some sand being deposited on the floodplain.

The flow option scenarios see some change in the frequency of flows in the large fresh to bankfull range. For sub-reach 27, increasing flows in this range may affect the rate of meander extension and meander cut-off although the magnitude of change relative to base case trajectory are likely to low.

In sub-reach 29, the increase frequency of bankfull flows may enhance the potential for an avulsion and channel straightening processes although the rate of change above the base case trajectory is likely to be low.

Table 6 Geomorphic impact score under current constraints and for the flow options scenarios (27)

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbanks	4.3	4.5	4%	4.4	4%
Bars	2.8	2.9	5%	2.9	4%
Cutoffs	2.8	2.9	5%	2.9	4%
Levees	0.6	0.6	-3%	0.5	-7%
Anabranches / Floodrunners (sub-bankfull)	1.8	1.9	8%	1.9	7%
Floodplain (> bankfull)	0.3	0.3	0%	0.3	-7%
Anabranches / Floodrunners (> bankfull)	0.3	0.3	0%	0.3	-7%
Average	**1.8**	**1.9**	**5%**	**1.9**	**3%**

Table 7 Geomorphic impact score under current constraints and for the flow options scenarios (29)

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbanks	4.3	4.5	4%	4.4	4%
Bars	2.8	2.9	5%	2.9	4%
Cutoffs	2.8	2.9	5%	2.9	4%
Benches	4.1	4.3	6%	4.3	5%
Sand slug	2.5	2.7	6%	2.7	5%
Anabranches / Floodrunners (sub-bankfull)	1.8	1.9	8%	1.9	7%
Floodplain (> bankfull)	0.3	0.3	0%	0.3	-7%
Anabranches / Floodrunners (> bankfull)	0.3	0.3	0%	0.3	-7%
Scour pools	2.8	2.9	5%	2.9	4%
Average	**2.4**	**2.5**	**6%**	**2.5**	**4%**

6. Limitations and Constraints

This desktop assessment is based on limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Rutherfurd, I.D., Budahazy, M. (1996). A sand management strategy for the Glenelg River and its tributaries, western Victoria. Report (Cooperative Research Centre for Catchment Hydrology); no 96/9. 1st September 1996.

streamology

Sub-Reach 28 Geomorphic Outline – Tumut Reach

Figure 1 Sub-reach map extent

1. Sub-reach position in catchment and general description

The sub-reach is situated on the Tumut River is 20 km upstream of the confluence with the Murrumbidgee River. The reach length is approximately 4.5 km. The town of Brungle is located to the East of the site. Nimbo Creek runs adjacent to the Tumut River in this reach.

2. Channel form and processes

a. Anthropogenic changes

The most significant anthropogenic change that will affect the channel form and processes is the water storage infrastructure upstream of the reach. As part of the Snowy Mountain Scheme, the Tumut River is impounded by six dams, which are all located upstream of the reach. These include Happy Jacks Dam, Tumut Pond Dam, Tumut Two Dam, Talbingo Dam, Jounama Dam, and Blowering Dam. Blowering Dam is the most downstream storage.

Desnagging works and the lopping of overhanging trees was undertaken in 1950s and 1960s. It led to bed degradation and exposure of further snags (Snowy Mountains Council Reports, 1972).

b. Historic changes based on the historical imagery

There were few observable changes in channel position between the 1966 aerial photographs and the 2021 Maxar satellite imagery. The riparian vegetation along Tumut River remains well established. There is an increase in the density of riparian vegetation along the banks of Nimbo Creek.

c. Forms (mainly based on LiDAR)

The channel has a lower sinuosity than the historic channel, based on evidence of relict oxbow and paleochannel features. The channel does not appear to be incised. Natural levee features are only evident in some sections of the reach. Tumut River in this reach has a higher bed elevation (0.5 to 1.5m) compared to Nimbo Creek.

d. Processes

The channel has been straightening based on evidence of relict oxbow lake features. Anabranches in this reach are established with new anabranches developing. The development of avulsions is possible at numerous locations in this reach. There is potential for a complete avulsion of the Tumut River into Nimbo Creek.

3. Floodplain form and process

e. Anthropogenic changes

The 1966 historical imagery shows extensive agricultural land use on the floodplains, indicating extensive clearing of native vegetation. Removal of floodplain vegetation will have implications for overbank flow velocities and anabranch development.

f. Hydrological connections

Nimbo Creek runs very close (less than 50m in some parts) to the Tumut River at numerous locations in this reach. Overbank flows from either of these waterways will likely connect both channels. Flood runners in the floodplains suggest hydrological connectivity between Tumut River and Nimbo Creek.

g. Form (mainly based on LiDAR)

The floodplain is bounded to the east and west by two elongated hills. The floodplain has numerous geomorphic features including flood runners, meanders, and oxbows.

h. Processes

Infrequent inundation and low sediment yields mean that rates of change are low. Flood runners are activated by high flows.

Representative Sub-reach: 28 **Historical Image**

Figure 2 Historic imagery (circa 19xx) of the sub-reach extent

Representative Sub-reach: 28 Digital Elevation Model

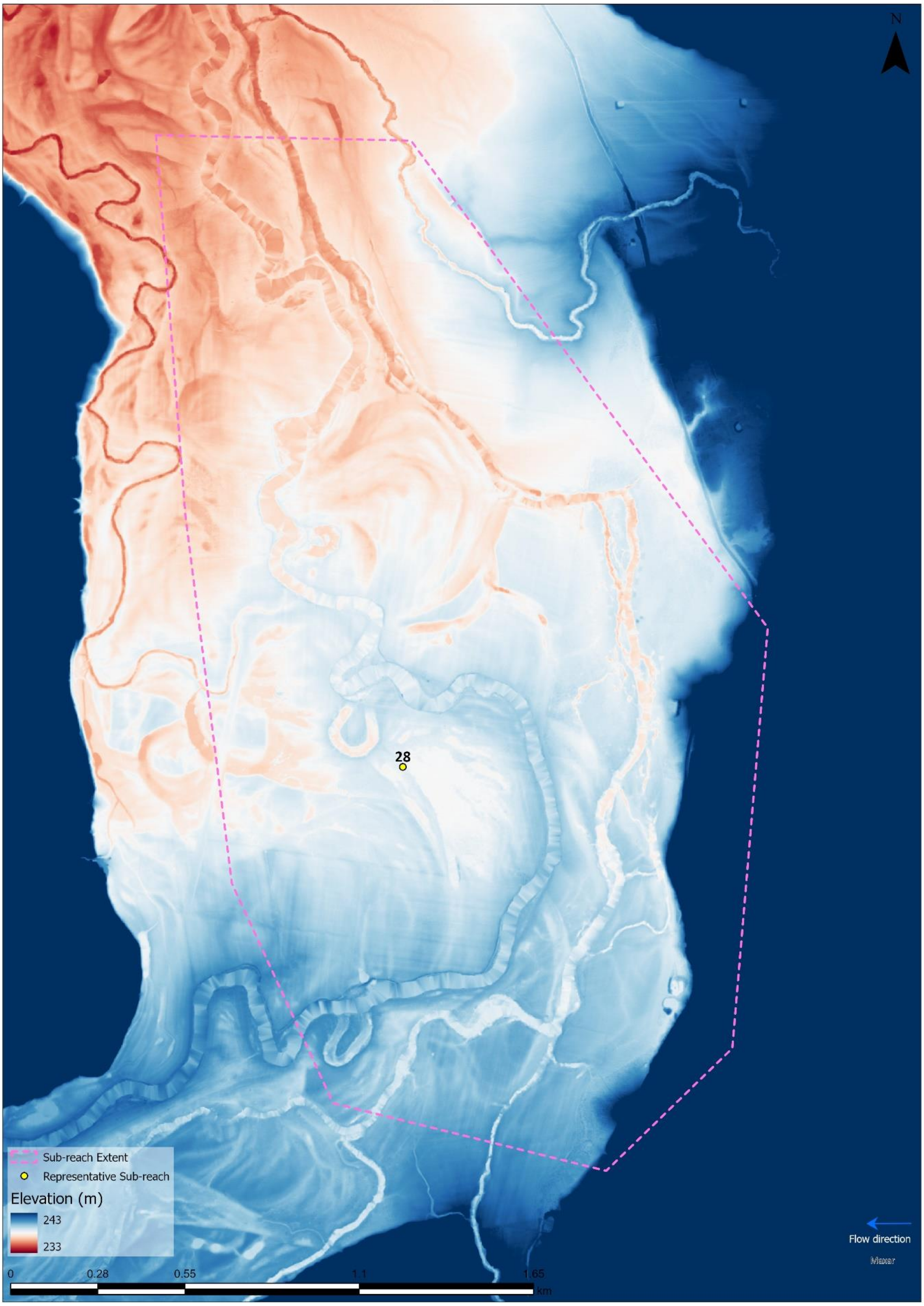

Figure 3 Lidar imagery of the sub-reach showing the different geomorphic features present

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic features and processes, sub-reach 28

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Floodplain (cutoffs)	Avulsion / meander migration / meander extension
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (>bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 28 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to these reaches are as follows.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an "impact score" for the main geomorphic features and processes relevant to this sub-reach.

The assessment for this reach is based on the proposed flow scenarios for the Tumut River.

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios (28)

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Cutoffs	Avulsion / meander migration-	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.99**	**0.27**	**0.05**	**0.00**
Likelihood (W40 events per year)		1.00	1.00	0.26	0.04	0.00
Likelihood (W32 events per year)		1.00	1.00	0.27	0.05	0.00

The base case trajectory of the reach (channel and floodplain) is likely to be ongoing river processes of lateral migration, meander extension and meander cut-off. The development of an avulsion of the Tumut River into Nimbo Creek is possible in a couple of locations. Changes in the flow regime as a result of the flow options scenario are minor and will not affect the rate of channel lateral migration, meander extension and meander cut-off.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbanks	5.3	5.3	0%	5.3	0%
Cutoffs	3.9	3.9	-1%	3.9	0%
Anabranches / Floodrunners (sub-bankfull)	2.9	2.9	-2%	2.9	0%
Floodplain (> bankfull)	0.2	0.1	-29%	0.1	-14%
Anabranches / Floodrunners (> bankfull)	0.2	0.1	-29%	0.1	-14%
Average	**2.5**	**2.5**	**0%**	**2.5**	**0%**

6. Limitations and Constraints

This desktop assessment is based on limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

Earth Tech 2004, Tumut River Management Report. 68-04-001. For Dept. of Infrastructure, Planning and Natural Resources.

Snowy Mountains Council (April 1972), Channel Capacity Investigations Lower Tumut River, Prepared by the Water Conservation and Irrigation Commission of NSW and the Snowy Mountains Hydro-electric Authority.

streamology

Sub-Reach 30 Geomorphic Outline – Jugialong Reach

1. Sub-reach position in catchment and general description

This sub-reach is located immediately downstream of the Town of Jugiong on the Murrumbidgee River. The reach length is approximately 6.5km. The reach has wide valley floor of about 900m bounded by steep hills with numerous gullies.

2. Channel form and processes

a. Anthropogenic Influences

This reach is significantly impacted by sand mining activities. There are three quarry pits within the reach, extracting sand and pebble materials. In addition, water storage infrastructure upstream of the reach will have an impact on the reach through changes to sediment budget along with flow seasonality, variability, and duration. Tanangara Reservoir and Burrinjuck Dam are located upstream of site. Other water storages on the tributaries upstream include Googong Dam, Corin Dam, Bendora Dam and Cotter Dam.

b. Historic changes based on the historical imagery

Few observable changes are noted in the channel between 1969 and 2021 with the latter imagery likely showing a lower water level, therefore exposing some sand slugs. There is an increase in riparian vegetation along the main channel and its anabranch.

c. Forms (mainly based on LiDAR)

The LiDAR shows evidence of flood chutes along the margins of the valley floor at the top of the reach. The straight section at the middle of the reach has a steep left bank of 1:2 slopes and height over 10m.

d. Processes

Meander extension is occurring at both the sharp meander bends in the reach resulting in the channel increasing its sinuosity over time. A vegetated avulsion channel is located at the end of the straight section of the middle reach. This avulsion channel is activated during higher flows but will eventually be the new main channel as the river takes a straighter and shorter course. Sand slugs are observed in various locations along the reach, increasing the sinuosity of the river during low flow conditions. Some of these sand slugs are partly vegetated.

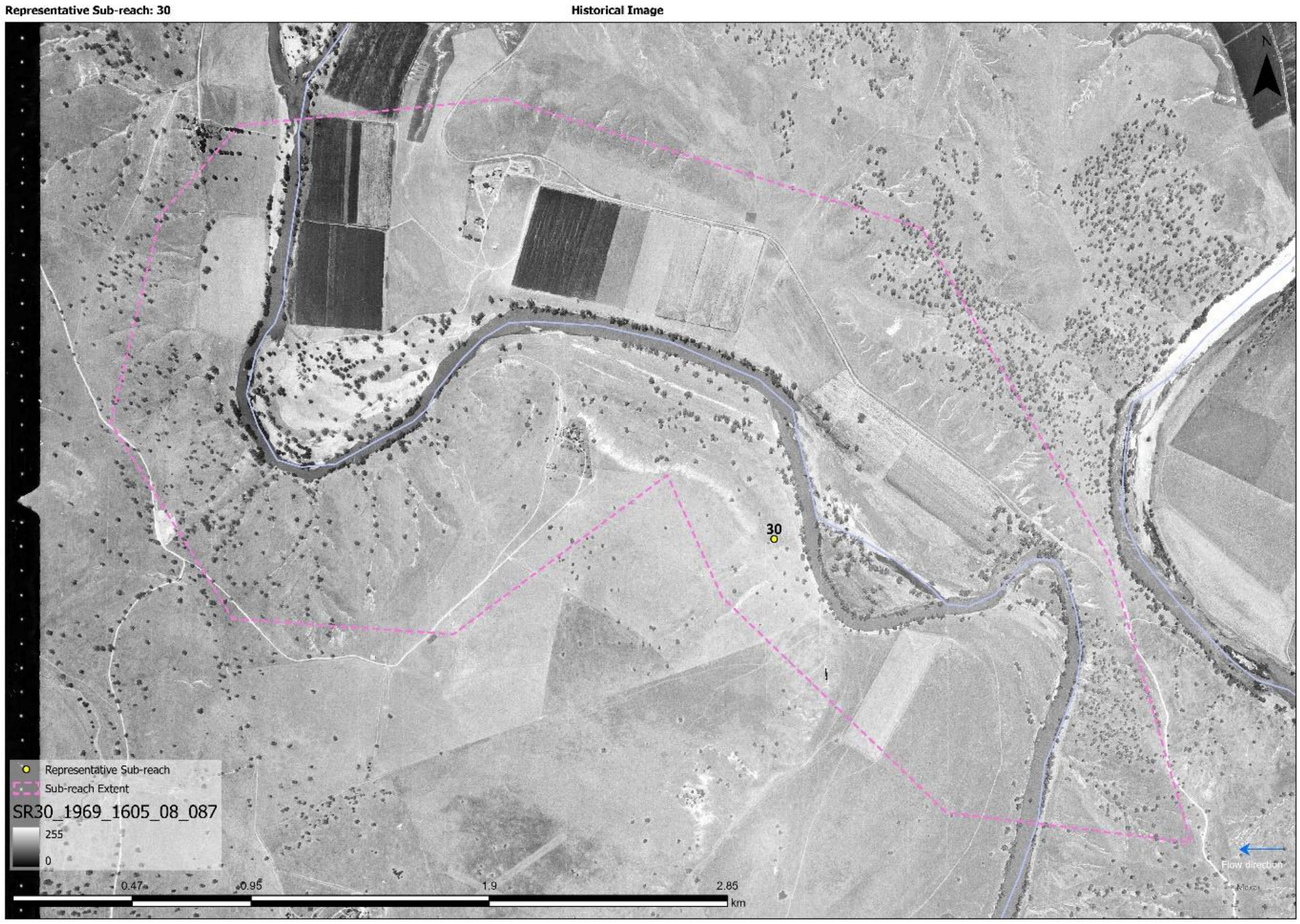

Figure 1 Historic imagery (circa 1969) of the sub-reach extent

3. Floodplain form and process

a. Anthropogenic changes

The 1969 back and white aerial photograph showed extensive agricultural activities on the floodplains. Some of these areas have been replaced sand mining activities in the 2021 Maxar satellite imagery. The sand mining activities is actively lowering the levels of the floodplain which are hydrologically connected during high flows. A high flow scenario will activate the floodplains and the locations of two of the quarries on the sharp inside meander bend will facilitate the development of an avulsion. This will lead to the channel short-circuiting and adopting a shorter and straighter course.

b. Hydrological connections

Inundation mapping shows that the floodplain is hydrologically well-connected during high flows (> 40,000 ML/d). The avulsion channel at the downstream end of the reach is active during flows > 22,000 ML/d. The flow assumes a shorter and straighter course with this flow path. Flows are distributed unevenly across the main channel and the avulsion channel with varying flows. The inundated quarries shown in the 2021 imagery is perhaps caused by activated floodplain during high flows.

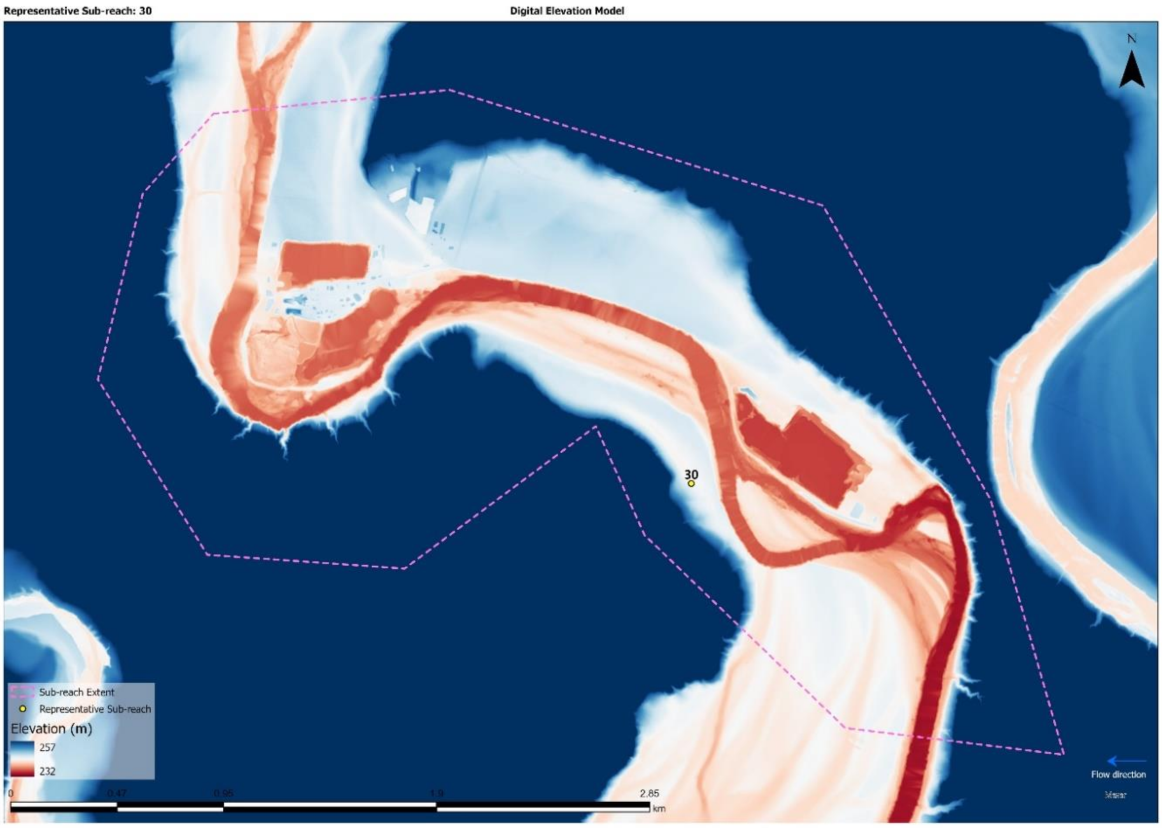

Figure 2 Lidar imagery of the sub-reach showing the different geomorphic features present

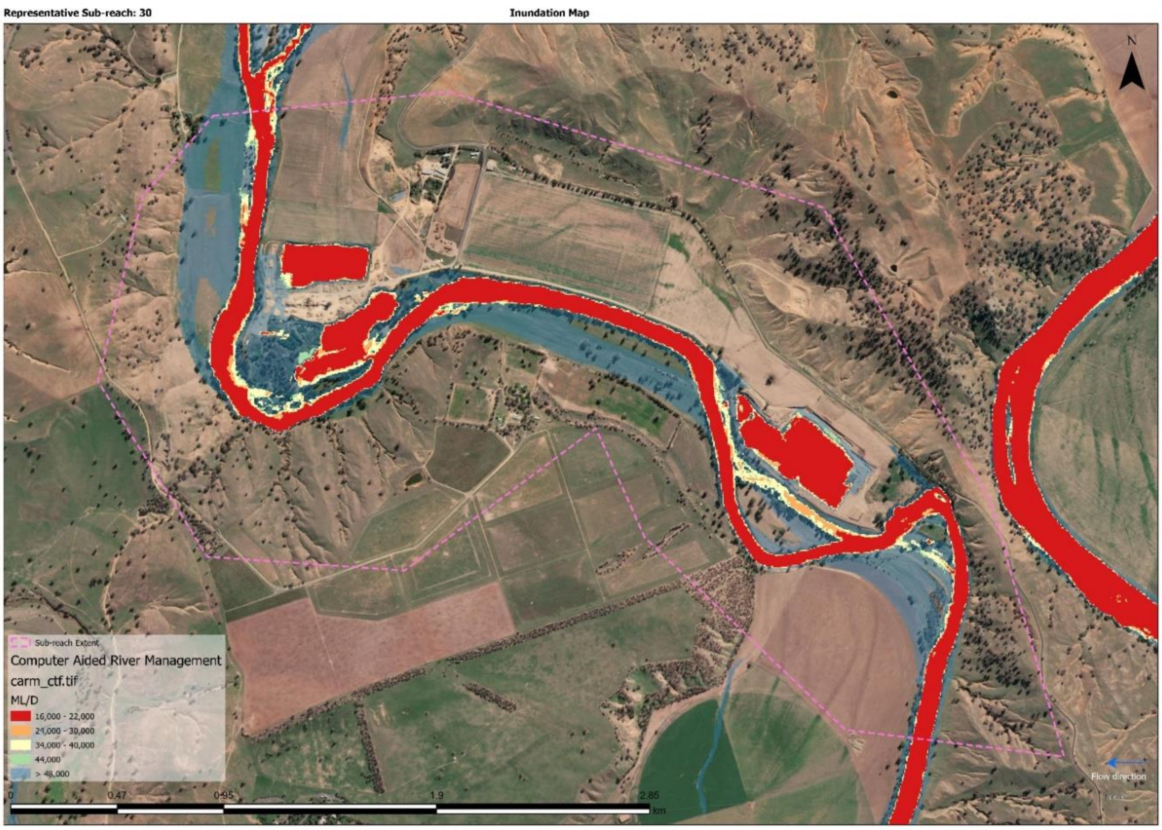

Figure 3 Inundation extents for the sub-reach for specific flow increments (based on RIMFIM modelled outputs)

c. Form (mainly based on LiDAR)

The LiDAR shows evidence of flood chutes along the margins of the valley floor at the top of the reach. The flat and wide valley floor also has an avulsion channel at the bottom of the reach as the channel adopts a short and straighter course.

d. Processes

The avulsion channel is activated by high flows (> 22,000 ML/d) across the floodplain and its proximity to the extraction pits mean that as the avulsion channel developed it may capture the pit within the channel.

The on-going removal of sand from the floodplain will lower the elevation of the floodplain and reconfigure the hydraulics of the active floodplains during high flows as the floodplain on the inside bend increasing the risk of pit capture as avulsion pathways develop. The removal of sediments will also limit the transport of sediments downstream.

4. Base case

The base case geomorphic features and processes are summarised in Table 1.

Table 1 Geomorphic features and processes, sub-reach 30

Geomorphic Feature	Process
Channel (riverbanks)	Erosion
Channel (sand slugs)	Transport
Floodplain (cutoffs)	Avulsion / meander migration / meander extension
Floodplain (sub-bankfull - anabranch/floodrunners)	Avulsion
Floodplain (>bankfull - anabranch/floodrunners)	Avulsion
Floodplain (> bankfull connection)	Sediment deposition

Each of these features and processes are linked to specific flow categories (e.g., regulated flows or bankfull flows) to different degrees (termed the 'level of association'). Further details on the flow linkages and level of association for different geomorphic features is contained in the main project report. The specific geomorphic features and flow linkages for sub-reach 30 are summarised in Table 3. The flow likelihood relates to the frequency of occurrence of the different flow categories.

5. Flow Options

The relaxed constraints flow options relevant to these reaches are as follows.

Table 2 Flow options relevant to this sub-reach

RRC Program Area	Flow limit options to be assessed (ML/d)	Areas for geomorphic assessments
Murrumbidgee	22,000 @ Wagga Wagga (current flow limit) 32,000 40,000	Murrumbidgee River and floodplain from Burrinjuck Dam to the Murray Junction, including the Lowbidgee floodplain and the Junction Wetlands, Beavers Creek, Sandy Creek, Old Man Creek, and associated tributaries. Tumut River below Blowering Dam to the junction with the Murrumbidgee River. Yanco Creek system extending from the junction of the Yanco Creek and Murrumbidgee River to the Edward River at Moulamein. Included Yanco Creek, Colombo Creek, Billabong Creek downstream of junction with Colombo Creek, Forest Creek, Forest Creek Anabranch and associated tributaries.

DPE has provided information on the change in frequency of flows within the different flow ranges under current constraints and for flow options scenarios. This information is summarised along with the flow associations to provide an “impact score” for the main geomorphic features and processes relevant to this sub-reach

Table 3 Overview of geomorphic features and flow linkages together with the likelihood of occurrence of the flows under current constraints and the flow options scenarios (30)

Geomorphic Feature and Process		Flow Associations				
		Small Fresh	Large Fresh	Bankfull	Moderate Overbank	Large Overbank
Riverbanks	Erosion	3	2	1	1	1
Sand slugs	Transport	1	2	3	3	3
Cutoffs	Avulsion / meander migration-	1	2	3	3	3
Anabranches / Floodrunners (sub-bankfull)	Avulsion	0	2	3	3	3
Floodplain (> bankfull)	Sediment Deposition	0	0	0	3	3
Anabranches / Floodrunners (> bankfull)	Avulsion	0	0	0	3	3
Likelihood (current constraints events/yr)		**1.00**	**0.53**	**0.13**	**0.11**	**0.00**
Likelihood (W40 events per year)		1.00	0.62	0.12	0.11	0.00
Likelihood (W32 events per year)		1.00	0.61	0.12	0.10	0.00

The base case trajectory of the reach (channel and floodplain) is likely to be ongoing river processes of lateral migration (bank erosion) within the floodplain. However, of greater concern is the development of the avulsion pathway and potential capture of the sand extraction pit currently on the floodplain.

Under the flow options scenarios change in the flow regime occur in the large fresh range and may increase the rate of change of these processes although the changes are not expected to be significantly above current rates of change. However, the geomorphic consequences under base case and flow option scenarios of capture of the extraction pits will be highly significant.

Table 4 Geomorphic impact score under current constraints and for the flow options scenarios

Geomorphic Feature	Impact Score by Scenario				
	Current Constraints	W40	% change	W32	% change
Riverbanks	4.3	4.5	4%	4.4	4%
Sand slugs	2.8	2.9	6%	2.9	4%
Cutoffs	2.8	2.9	6%	2.9	4%
Anabranches / Floodrunners (sub-bankfull)	1.8	1.9	9%	1.9	7%
Floodplain (> bankfull)	0.3	0.3	0%	0.3	-7%
Anabranches / Floodrunners (> bankfull)	0.3	0.3	0%	0.3	-7%
Average	**2.0**	**2.1**	**5%**	**2.1**	**4%**

6. Limitations and Constraints

This desktop assessment is based on limited historical imagery, LiDAR of a single timestamp and contemporary imagery. This assessment may not provide a comprehensive analysis of processes.

7. References

None.