# Lower Goulburn Floodplain Study

GEOMORPHOLOGY

- Final

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# 1. Introduction

The lower Goulburn River floodplain and Deep Creek system have been the focus of numerous investigations as part of the Lower Goulburn floodplain rehabilitation scheme. The rehabilitation scheme considers reflooding the northern section of the Goulburn River floodplain through Loch Garry and channelling overflows through the existing floodplain waterways (i.e. the Deep Creek system). The geomorphology of this region has been well documented (e.g. Bowler, 1976; Cameron McNamara, 1987; Erskine *et al.*, 1993; SKM, 1998) with the floodplain channels reported as relics of ancestral and prior streams that formed thousands of years ago. Fluvial reworking of these streams has resulted in the contemporary Deep Creek system, which reflects characteristics of the ancestral rivers of the Riverine Plain.

Since European occupation, irrigation development and regulation of the Goulburn River has reduced the frequency and magnitude of flows over the lower floodplain. Consequently, the rate of adjustment of floodplain channels has altered. Reintroducing flows to the floodplain may have numerous consequences including altered erosion rates and possible avulsion of the Goulburn River.

This project investigates the likelihood of an avulsion occurring as a result of increasing flows to the floodplain channels. The study deals with the section of the lower Goulburn River floodplain from Loch Garry to the Murray River and focuses on the effluent channel systems of Deep, Sheepwash, Skeleton and Bunbartha Creeks along the north bank of the river.

Investigations into historic and present day morphology, the rates of geomorphological change, soil types and critical shear stress of the soil in the Deep Creek system provide information on bed and bank stability. These results are compared with those from similar tests conducted on the Goulburn River. Based on the analysis of these results an assessment of possible avulsion from the Goulburn River to Deep Creek under the proposed Lower Goulburn Floodplain management scheme is made.

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# 2. Lower Goulburn floodplain

Rising in the Great Dividing Range, the Goulburn River drains a catchment area of some 16,200 km$^2$ before debouching into the Murray River near Echuca. Flow in the lower Goulburn is highly regulated by major upstream storages, in particular Eildon Weir (3,400 GL) and Goulburn Weir (25 GL). These storages and associated diversions combine to reduce the average annual basin flow to about 2,000 GL (SKM, 1998). Lake Eildon supplies water to the irrigation areas in northern Victoria.

In its lower reaches, the Goulburn River flows through a broad floodplain (some 2 km wide) that forms part of the Riverine Plain. The modern channel is sinuous, with steep banks composed of fine sands and silts with high percentages of clay (Erskine *et al.*, 1993). Meander scrolls and oxbow lakes indicate that the river has migrated extensively in the past; a trait of the river that will no doubt continue into the future.

The floodplain of the lower Goulburn River has been extensively modified. Clearing for agriculture and grazing has occurred on both sides of the river. The south side includes irrigation and drainage infrastructure with its network of roads. On the north side, dryland grazing and agriculture occur on the floodplain with a small proportion of irrigation.

From Loch Garry downstream the near channel floodplain of the Goulburn River is separated from the broader floodplain by natural and artificial levees. Flood flows escaping from the river channel on the north bank drain to the north away from the river, following the slope of the Riverine Plain to the Murray River. A number of ephemeral waterways (Bunbartha Creek, Skeleton Creek and Sheepwash Creek) collect these breakaway flows, and local floodplain runoff, and convey them to Deep Creek (an extension of Bunbartha Creek) which meets the Murray River about 7 km downstream of Barmah.

## 2.1 Floodplain evolution

The Goulburn River occupies a trench in resistant clay (the Shepparton Formation) that was cut by two larger ancestral river systems (the Kotupna and Tallygaroopna streams). The modern river has flowed in its present course for the past 10,000-15,000 years (Erskine *et al.*, 1993). Throughout much of the study area, the Goulburn River is now bordered by a near channel floodplain, approximately 2 km wide. This corresponds generally to the meander belt of the ancestral Kotupna course.

The contemporary floodplain is punctuated by former stream courses, lakes, levees, wetlands and dunes. The remains of a previous Goulburn River channel are now marked by Wakiti Creek while an even earlier course, abandoned perhaps 25,000 years ago, ran from Shepparton via Bunbartha and Kaarimba to the present course of the Broken Creek near Kempsters Road. The Goulburn River may have occupied more than one of these ancestral streams at one time and each has left its own complex pattern of changing meanders and breakaways (SKM, 1998).

The Riverine Plain, as described by Bowler (1976), is a large depositional zone associated with the Murray River and its tributaries. The sediments of the Riverine Plain consist of river and floodplain deposits, swamp and lake deposits, and associated bordering dune and lunette deposits (e.g. Barmah Sandhills). These prehistoric landscape features have become the sites of modern wetlands and continue to influence the course of flood flows from the Goulburn to the Murray River. The surface sediments of the Riverine Plain date from the Late Tertiary to Quaternary.

### Barmah Sandhills

An important feature of the lower Goulburn floodplain is Lake Kanyapella, an ancient lake which is now dry. The lake formed as a result of the tilting of the Cadell block which diverted the Murray River at its northern end and formed Kanyapella Lake from the Goulburn River at its southern end (Thoms *et al.*, 1998). The lake drained between 25,000 to 13,000 years ago when the Goulburn River cut a new path around the block. The lake led to the creation of the Barmah Sandhills, a lunette on its northeastern shore. Flows from the present Goulburn River can only pass through three gaps in the Barmah Sandhills:

- at Yambuna on the present course of the Goulburn River (Yambuna Choke);
- through a flood course associated with the Madowla Lagoon; and
- at high river stage, along Yambuna Creek to Warrigal Lagoon and Kanyapella Basin.

The latter two gaps are now blocked by levees. Flood flows also find their way through the sandhills via overflows to Deep Creek and the Murray River. Flow control in the Murray River is caused by a narrow gap in the Barmah Sandhills that backs up the river during floods, increasing discharge to the Edward River and simultaneously inhibiting the escape of flood waters from Deep Creek (SKM, 1998).

## 2.2 Levees and flood regulation

Natural levees are well developed on the northern side of the Goulburn River below Loch Garry and along Wakiti Creek. The levees here, indicate the predominant direction of spill from the river resulting from the tilt of the floodplain from the Cadell fault (Cameron McNamara, 1987). The levees generally act to keep flood waters that leave Loch Garry from re-entering the river or the Wakiti Creek system. The natural levees along the Tallygaroopna system and the Broken Creek course prevent floodplain flows from leaving the Deep Creek system to the north. As a result, floodwater leaving the river at Loch Garry or in the vicinity of the Deep Creek Outlet to Bunbartha Creek is effectively channelled down the Deep Creek system to the Murray River.

The south side of the Goulburn River does not have well defined natural levees although some levee development is evident. The lower levees on this side would have resulted in floodwaters spilling to the south. This would have continued unless an alternative course of the river developed via the present Deep Creek. Once a new course had been established, the southern areas of the floodplain would have become isolated from flood spills (Cameron McNamara, 1987).

Under natural conditions flows exceeding the bankfull capacity of the lower Goulburn River would have been lost to the lower parts of the floodplain, with breakouts occurring at many locations along the river. According to Cameron and McNamara (1987) channel capacity between Loch Garry and the Murray River shows a progressive downstream decrease, indicating geomorphological adjustment to the progressive loss of flows.

Now the Goulburn River downstream of Shepparton is bordered by an extensive system of artificial levees. Continuous levees have been constructed on both sides of the river for most of the distance between Shepparton and Yambuna. Downstream, the levees tend to occur on at least one side of the river (Cameron McNamara, 1987). Outlet structures have been constructed to control overflows (e.g. Loch Garry Regulator, Hancocks Creek Regulator).

The artificial levee system is forcing larger volumes of flow much further downstream along the alignment of the main channel of the Goulburn River than would have occurred under natural conditions. In a few places the levees are situated close to the river on both banks, leaving only a very narrow strip of floodplain in between. While the near-channel floodplain has a natural width of ~2 km (with large floods spreading out beyond this area), the floodplain between the levees is only 700 m wide downstream of Loch Garry and 500 m near McCoy's Bridge (SKM, 1998). Larger flows and greater flow depths occur in the main channel and within the levees, leading to increased streampower and thus potentially increased erosion (Cameron McNamara, 1987).

The continuous levees on the northern side of the river terminate well upstream of the Yambuna Choke. Overflow to Deep Creek still occurs, but because less flow is lost through natural outlets upstream, larger volumes are discharged via the downstream outlets than would have been the case under natural conditions. The limited number of overflow sites in the levee system has led to unnaturally high concentrations of flow at individual outlets. This may have contributed to scour observed in the vicinity of the Loch Garry and Hancocks Creek regulators as well as in Tessie, You You, and Deep Creeks downstream of You You Creek.

Some major distributary overflow paths have been blocked by the levee system. This may have serious consequences for river stability, as observed by Cameron and McNamara (1987), at a former overflow watercourse to Wells Creek from Dunnmores Creek near Undera North.

## 2.3 Channel morphology

Human activities have significantly affected the geomorphology of the lower Goulburn River. Indeed Erskine *et al*. (1993) argued that the present adjustment of the Goulburn River is largely a response to the construction of Eildon Weir and the regulation of flows. Other local effects include levee construction, bank stabilisation works and clearing.

The lower Goulburn River is an anastomosing alluvial river with banks consisting largely of unconsolidated sediments including sands, silts, clays and some gravels. Localised outcrops of semi lithified materials are apparent in some areas. The modern Goulburn River is reworking sediments left behind by its ancestral streams. The newer sediments are more erodible than the older heavy clays and partly consolidated rocks of the most ancient stream deposits. In places, these older deposits now provide bed-level control of the modern river and influence bank processes and erosion rates (SKM, 1998).

The riverbed is largely composed of Shepparton Formation clays with occasional outcrops of cemented gravels and sands (probably courser bed sediments of the ancient Kotupna system, after Erskine *et al.*, 1993). Sands are transported along the bed with the occasional point bar formed in this material. However, most banks on the inside of meander bends do not support a point bar. According to Erskine *et al.* (1993) bank erosion and bed deposition have been negligible over the last century. However, while the river bed is generally stable throughout the study area, reaches from Loch Garry to Connolly's Cut and from Hancocks Creek to Wakiti Creek are less stable. Numerous artificial cutoffs have been constructed in these reaches. Some of these cutoffs are fully developed, resulting in local steepening of the stream profile. Other cutoffs are still progressing and will potentially lead to further steepening if they continue to develop. Six of the cutoffs have been treated with bed control structures but at Connollys Cut there is particular concern that localised deepening will eventually de-stabilise the banks.

### 2.4 Avulsion processes

Anastomosing streams such as the lower Goulburn River, are characteristic of stream patterns of the Riverine Plain (Butler *et al.*, 1973). While these rivers are subject to the usual geomorphological processes of aggradation, deposition and meandering they are also prone to avulsion. Avulsion is the process whereby a river abandons part of its course in favour of a new one. Development of avulsions is a natural long-term process and numerous avulsions have occurred along the Goulburn River (Erskine *et al.*, 1993).

Processes controlling avulsions include increased sinuosity, gradient reduction, sediment deposition, bench formation, tree growth and log jams (Schumm *et al.*, 1996). Schumm, *et al*. argued that as channels in lowland Australian environments become more sinuous, they generally become less efficient and less stable. Eventually they avulse and a new anabranch develops. Young channels (i.e. those that have recently avulsed) are characterised by low sinuosity and large meander wavelengths. They tend to have steep gradients, are unstable and convey large flood discharge. As the channels mature, they widen and become shallower due to aggradation. Older channels are relatively stable and have high sinuosity, small meander wavelengths, gentler gradients and small bankfull flows. The oldest abandoned anabranches are now only manifested as discontinuous depressions on the floodplain.

Through time, as the channels evolve, stream courses on the floodplain progressively become less hydraulically efficient. Overbank flow becomes more frequent and alluvial ridges and natural levees form as a result of deposition. In the case of the Goulburn River, the main channel occupies the highest part of its floodplain, with the bed of Deep Creek marking the lowest point. Hence, changes to the course of the Goulburn River across the Riverine Plain are inevitable in the long-term. Diminishing downstream channel capacity, eroding floodpaths and distributary creeks potentially encourage the development of alternative courses capable of diverting the river by avulsion. This risk is increased if the ground surface is exposed by clearing or vehicle damage, or if flood flows are concentrated as a result of drainage or flood mitigation works (SKM, 1998).

Research by Judd (2005) on avulsion processes indicates that avulsions initiate at a downstream feature and then migrate upstream to capture the main channel. Judd noted that erosive forces on a developing avulsion, and more generally on nickpoints, increase with flow rate down the avulsion to a maximum rate and then decrease. This is due to the non-uniform nature of flow over an erosion feature. In a case-study on a developing avulsion on the Ovens River, Judd found that the most erosive forces were developed during flows with a recurrence interval of two years. Then, taking account of the relative frequency and duration of events, he found that most erosion occurred during floods with a recurrence interval of six to eight months. This is perhaps equivalent to the most effective discharge studied by Tilleard (2001). However, in the case of avulsions on the Ovens, the most effective flow not only has a higher frequency and duration than larger flows, it also exerts a higher force.

The natural topography of the floodplain, with the Goulburn River perched on an alluvial ridge and Deep Creek situated in a much lower part of the floodplain, predisposes the river to an avulsion into the Deep Creek system. Channel evolution occurs on a time frame that can be measured in thousands of years. However, the time necessary for an avulsion cycle to occur is highly variable. The occurrence of the next avulsion in the lower Goulburn River and floodplain is unlikely to happen within the next 100 hundred years (Erskine *et al.*, 1993; Schumm *et al.*, 1996).

A good example of avulsion on the Goulburn River can be found near McCoy's Bridge. Wakiti Creek is an old course of the Goulburn River which was abandoned as the result of an avulsion into the contemporary course. Radiocarbon dates presented by Bowler (1976) suggest that the avulsion probably occurred within the last 10,000 years, as the transition from the Kotupna system to the modern Goulburn River occurred sometime between 10,000 to 15,000 years ago.

The natural topography of the floodplain, with the Goulburn River perched on an alluvial ridge and Deep Creek situated in a much lower part of the floodplain, predisposes the river to an avulsion into the Deep Creek system. The development of the levee system has reduced the opportunities for overflows to occur to the upstream parts of the Deep Creek system, putting considerable pressure on overflows at the lower end. Changes in the water level regime of the Murray River as the result of flow regulation may have affected the base level for Deep Creek and is also likely to be a contributing factor (SKM, 1998).

# 3. Deep Creek

The lower end of Deep Creek is a single-thread low sinuosity channel. The cross-section of the channel is trapezoidal and generally symmetrical (~ 6 m deep by 30 – 35 m wide). There is little evidence that a meandering planform has started to develop with little point bar deposition within the channel. The lack of meander development suggests that Deep Creek is relatively youthful, compared to the Goulburn River itself (see Schumm *et al.*, 1996).

Exposed tree roots were observed on both banks indicative of channel widening (Figure 3.1). The widening appears to be relatively uniform with the degree of root exposure similar on trees of similar age. However, locally we observed that the bank receded between tree root wads. This is indicative of the trees either increasing the erosion resistance of the banks or protecting the banks from erosive forces. The bank material in the lower Deep Creek is reasonably erosion resistant consisting of clay sands and clay loams with the material fining up the bank. However, there are sections of bank that are dominated by clay. These clayey bank sections protruded further into the channel and are therefore likely to be more erosion resistant than the more usual bank profile formed in clayey sand.

**Figure 3.1: Evidence of scour on the banks of lower Deep Creek.**

Further upstream at the confluence of Skeleton and Sheepwash Creeks with Deep Creek the channel morphology is similar to lower Deep Creek but the major channels are narrower and shallower (~30 m wide by 5 – 6 m deep). At the confluence of these channels we noted interesting morphology indicative of the developing nature of these alluvial channels. The bed of Sheepwash Creek is perched some 3 m above the bed of Skeleton Creek (Figure 3.2). Moreover, on the face of the steep transition from Skeleton to Sheepwash Creek there was evidence of more recent erosion.

**Figure 3.2: Confluence of Skeleton and Sheepwash Creeks (looking from the bed of Skeleton Creek upstream into Sheepwash Creek).**

Furthermore, a nickpoint was observed in the bed of Skeleton Creek just upstream from the confluence with Sheepwash Creek. The nickpoint was about 1 m high and had clearly migrated up the bed of Skeleton Creek. This morphological evidence indicates the beds of the Deep Creek system are deepening via the headward migration of steep localised nickpoints. Longer, lower gradient knick zones observed in other locations may also be causing deepening. We hypothesise that the location of the nickpoint at the junction the two creeks is controlled by the combined discharge of the two creeks below the confluence. The nickpoint has eroded to the point (just beyond the confluence) where the (current) flow regime in Skeleton Creek, alone, does not have the erosional capacity to propagate the bed deepening further up the system.

At another confluence in this reach (that of Deep Creek and an unnamed anabranch to the south) the channel of the unnamed anabranch is perched some 4 m above the invert of Deep Creek. In a similar process to the downstream end of Sheepwash Creek, the face of the steep transition from the unnamed anabranch to Deep Creek suggests that there has been relatively recent erosion and that erosion may be ongoing.

Further upstream, particularly just below the Murray Valley Highway, a different eroded feature along Sheepwash Creek and a tributary of Skeleton Creek was observed. It was noted that in areas where, in a downstream direction, the floodplain transitions from a relatively flat floodplain with an ill defined channel to that of a well defined channel some 3 – 4.5 m deep with and a bankfull width of 25 – 50 m. The morphology of the channel bed in this transition zone was suggestive of highly erosive flow conditions and in a relatively erosion resistant floodplain. At this point, well defined scour holes were noted around woody debris and mature trees. These bed features suggest erosion forces applied in this transition zone are sufficient to undermine mature River Red Gums.

Just downstream of the transition zone into Sheepwash Creek at the Murray Valley Highway we noted that the roots of old River Red Gums within the bed of the well defined channel have been exposed by an estimated 0.5 – 0.75 m of deepening. This suggests that erosion of the bed of this avulsion channel may have been relatively slow over a hundred or more years. However, just upstream, within the transition zone, we noted younger trees that may be 15 to 20 years old where root exposure had occurred. From this we speculate that well defined channels of consistent morphology are not eroding rapidly whereas steep transitions floodplain to channel induce erosion.

At the Murray Valley Highway, Skeleton Creek and Deep Creek are still well-defined channels, although shallower than lower Deep Creek, at 4 – 4.5 m but still 25 – 35 m wide at bankfull. However, much of this width is associated with what we considered palaeochannel features and the compound nature of the cross-sections. The width of the incision due to the reoccupation of the palaeochannel is 10 – 15 m (or less in some areas). At both these sites on the Murray Valley Highway we perceived that these had been eroded within the past 50 years with an estimated 0.3 m of bed degradation at Deep Creek in this time frame.

**Figure 3.3: Example of compound channel morphology from lower Deep Creek.**

Upstream of the Murray Valley Highway we also noted avulsion tributaries that lead from the Goulburn River and extend across to Deep Creek. The dimensions of one channel was 10 m wide by 1 m deep, whilst the other was 10 – 15 m wide and around 2.5 m deep. We noted that the larger tributary is of considerable age, perhaps similar to Deep Creek itself and appears to have been eroded slightly in the past 50 years. Such tributaries are likely to deepen with Deep Creek depending on the magnitude, frequency and duration of spills from the Goulburn River.

Further upstream at McLellands Road we noted that Sheepwash Creek is a series of scour features which appear to be inset into palaeo features, not dissimilar to what was found downstream at the Murray Valley Highway.  Again, scour is prevalent around woody debris.

At Skeletons Creek near McLellands Road we found another steep transition not dissimilar to that found on Sheepwash Creek downstream of the Murray Valley Highway.  Again, we found scour around mature River Red Gums in what appeared to be erosion resistant floodplain material.  We also noted minor nickpoints on this steep transition, all indicative of a zone that is subject to erosive flow conditions.  Skeleton Creek was again of compound morphology, possibly representing a more recent reoccupation of a palaeochannel.  We speculate that, unlike the transition zone to the floodplain just upstream, there has only been minor erosion on this well defined section of Skeleton Creek in the past 100 years.

The Deep Creek system downstream of McLellands Road exhibits an unusual and complex morphology.  The overall channel width was 25 – 30 m with a depth of 2.5 – 3 m and diverse scour morphology inset into the channel.  The morphology consisted of scour holes on the channel sides and pronounced scour pools within the channel.  Separate scour features were sometimes set side-by-side within the overall channel.  We are unsure of what is causing this morphology in what we consider to be, but have not confirmed, a relatively localised area.  Scour around woody debris and trees may explain part of the diversity.  However, it is likely to also be influenced by local variations in the erosion resistance of floodplain material.

# 4. Fieldwork

Beyond describing the morphology of the lower Goulburn River's floodplain channels, we undertook a number of field-based investigations. The entire Deep Creek system was systematically investigated to assess channel processes and the risk of future avulsion. At two representative sites, on lower Deep Creek, we also undertook detailed sampling to assist us in characterising the sediments of the Deep Creek system. Field sampling consisted of:

1) particle size analysis of alluvium;
2) *in situ* submerged jet testing to measure erosion resistance of the alluvium on the toe and banks of Deep Creek; and
3) triaxial shear testing of undisturbed samples to assess the mass stability of the banks of Deep Creek.

## 4.1 Particle size analysis

Particle size analysis was conducted on samples from the two representative sites and an additional one site further upstream on Skeleton Creek (Table 4.1, Appendix A). The results indicate a slight fining of sediments with distance upstream along Deep Creek. Site 1 consists of fine to medium grained clayey sand at the toe and fine to medium grained silty sand on the bank. Site 2 is characterised by fine sandy clay on the toe and fine to medium silty clay on the bank. PSA conducted on the Skeleton Creek bed sample showed a silty clay soil type.

**Table 4.1: Deep Creek boundary sediments.**

| Site | Sample description |
|---|---|
| Site one toe | Clayey sand, fine to medium grained |
| Site one bank | Silty sand, fine to medium grained |
| Site two toe | Sandy clay, with fine to medium sand |
| Site two bank | Silty clay, with fine to medium sand |
| Skeleton Creek bed | Silty clay, with fine to coarse sand |

The results of our analyses are consistent with other results recorded in the area (e.g. Bailey and Rutherfurd, 2005) and are typical of alluvial material found in lowland environments such as the Riverine Plain. These sediments tend to be cohesive and are relatively erosion resistant when compared to banks formed in non-cohesive sediments. The erosion of cohesive banks generally occur as a result of mass wasting, fluvial entrainment and subaerial processes (Abernethy and Rutherfurd, 1998). Indeed, the subaerial processes of desiccation, weathering and cracking (due to shrink swell properties of the clay) are important preparation processes that prime the bank material for erosion by fluvial scour (Lawler, 1992). Mass wasting generally occurs when some critical combination of bank height and angle is exceeded. Fluvial scour either degrades the near-bank bed (leading to higher banks) or erodes toe of the bank laterally (leading to a steeper bank profile) or a combination of both.

## 4.2 Hydraulic scour

This project investigated sediment characteristics in the Deep Creek system by using a submerged jet apparatus to determine the critical shear stress of the bed and bank materials. The shear resistance of natural riverbeds and banks is notoriously difficult to calculate (Hanson, 1991). However, in their review of the available methods Bailey and Rutherfurd (in prep.) argued that the submerged jet apparatus served to give repeatable results and was suitable for applications in studies of the erosion of natural riverbanks. This apparatus works on the principle of a submerged radial wall jet of constant velocity distribution producing a shear stress. A relationship between the jet diffusive properties and the distance from the jet orifice to the bed surface supplies an estimate of the boundary shear stress on the surface material ($\tau$). This relationship, in conjunction with a hyperbolic asymptotic relationship formulated by Blaisdell *et al*. (1981), allows the results from the jet device to estimate the equilibrium depth of scour and resulting critical shear stress ($\tau_c$) of the sediment. This apparatus has been used by numerous studies in the US and Australia (see Allen *et al.*, 1999; Hanson *et al.*, 2002; Wynn, 2004; Bailey and Rutherfurd, 2005).

The submerged jet device consists of a steel circular base tank driven into the test surface and pinned in place (Figure 4.1). Latched to the base tank is a lid (sealed with a rubber gasket), on which is mounted a pressure gauge, jet tube and point gauge. Water is pumped to a header tank which is connected via a hose to the base tank of the testing apparatus. It is necessary to have a supply of water for the operation of the submerged jet testing device. Further details of the testing procedure are reported by Hanson *et al*. (2002).

**Figure 4.1: The submerged hydraulic jet device in situ.**

Tests require a relatively flat surface cleared of debris. Once the surface is clear, the base of the jet tester is set on the surface and hoses connected. Water is subsequently supplied to (and fills) the base tank, with a deflector plate held in front of the jet nozzle. When the base tank is full the deflector plate is removed from the trajectory of the jet and testing commences. Testing results in scour of sediment below the jet with measurements of scour taken at a range of increasing intervals (i.e. 1 minute, 2 minute, 5 minutes and 10 minutes) over a 40 minute period. Figure 4.2 shows the resulting scour hole from a 40 minute test.

**Figure 4.2: Scour hole produced during 40 minute test.**

Six tests were conducted at two sites on the lower Deep Creek. Tests were made on material at the toe and bank face. Our site locations were constrained to the lower Deep Creek as further up the system the creek bed is dry. The sites were chosen after initial investigations of the Deep Creek system showed relatively uniform bank material that appeared representative of the lower Deep Creek.

The results for critical shear stress showed a large scatter of values ranging from 0.77 to 1.96 Pa with a mean value of 1.42 Pa (Table 4.2). These values are consistent with similar tests conduced by Bailey and Rutherfurd (2005) on the lower Goulburn River. As shown in Table 4.2, the Goulburn results are also scattered widely with a mean value of 1.24 Pa.

A review of previous test results from differing environments by Bailey and Rutherfurd (in prep.) shows that such scatter is the rule rather than the exception with some data sets varying by up to six orders of magnitude. Reasons for the wide variations in sediment shear resistances are variously cited as: varying degrees of subaerial exposure; the amount of cracking along bedding planes; water content; pore water pressures; rapid changes in bulk density with depth from the sediment surface; and the reinforcing influence of roots.

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**Table 4.2: Submerged jet test results.**

| Goulburn River[1] | | Deep Creek | |
|---|---|---|---|
| Test | $\tau_c$ (Pa) | Test | $\tau_c$ (Pa) |
| 1 | 1.57 | 1 | 1.20 |
| 2 | 0.05 | 2 | 1.72 |
| 3 | 0.63 | 3 | 0.80 |
| 4 | 0.39 | 4 | 0.77 |
| 5 | 0.79 | 5 | 2.08 |
| 6 | 0.11 | 6 | 1.96 |
| 7 | 2.46 | | |
| 8 | 1.47 | | |
| 9 | 3.66 | | |

[1]From Bailey and Rutherfurd (2005).

Unfortunately, the scale of the previous hydraulic modelling of the site precludes a thorough understanding of the boundary shear stresses imposed on the Deep Creek boundary sediments during overbank flows from the Goulburn River.  However, if we make some assumptions of channel morphology, based on our field observations we can calculate a rough estimate of boundary shear stress.  Boundary shear stress ($\tau_b$) is given by:

$$\tau_b = \rho g R S \qquad (1)$$

where ρ is the density of water, g is acceleration due to gravity, $R$ is the channel's hydraulic radius and $S$ is the gradient of the channel bed.  From our observations of the Deep Creek channel, in the vicinity of our test sites, we can assume an average bankfull channel width of 35 m, an average bed width of 20 m and average depth of 5 m.  Assuming a symmetrical channel, these dimensions yield an average cross-sectional area ($A$) of ~137 $m^2$ and a wetted perimeter ($P$) of ~38 m and we can set $R$ to an average of 3.62 m (where $R = A/P$).  From the longitudinal profile of lower Deep Creek[1] we have further assumed an average bed gradient of 0.00021 m/m.  Combining these values in Equation 1 yields an average boundary shear stress of 7.43 Pa.

That our estimate of boundary shear stress, imposed by bankfull flow, is up to one order of magnitude higher than the critical shear stresses of the banks suggests a much more rapid rate of change than our field observations indicate.  However, fluvial scour is an extremely localised phenomenon influenced by many variables.  The duration of erosive flow is extremely important, as even very erosive flows that only act for a short period of time cannot entrain significant amount of cohesive sediment from the channel perimeter.  In addition, as demonstrated above, there are marked variations in the erosion resistance of boundary sediments.  Some of these variations are due to the properties of the material but in natural systems, the combined effects of vegetation and subaerial processes also wield a profound influence on the erodibility of channel boundary

[1] See "Sheepwash, Skeleton, and Deep Creeks cross-section and longitudinal section comparison Lidar (2002) versus historic data (1982) Sheet 7/7" prepared by LICS for GBCMA.

sediments. Bailey *et al.* (in prep.) present a conceptual model of the interaction between flowing water and root impregnated alluvium. They show a range of root influences from reinforcement of the material to turbulence-induced scour.

Regardless of particular local effects that give rise to the extremely complex flow patterns found in natural channels, our results demonstrate that, in broad terms, the average shear stress imposed on the channel boundary should give rise to general erosion of the channel perimeter during bankfull flow. This contention is certainly supported by our field observations. There are signs of fluvial scour everywhere along the Deep Creek system. However, nowhere can we see any evidence of rapid widening or lateral migration of the channels. Our overwhelming impression of bank erosion in these channels is a slow tendency to channel widening through parallel bank retreat. The riparian vegetation of this reach appears to a vital element in the ongoing protection of the channel; further degradation of the riparian zone should be definitely avoided (see also Abernethy and Rutherfurd, 1998).

### 4.3 Bank stability

Lawler (1992) suggested that where there is a gradual downstream increase in channel size, there should be a point where bank height exceeds some critical value for the boundary material and mass failure assumes dominance in the erosion process. Thorne (1991) argued that when this occurs an important geomorphic threshold is crossed and the thrust of channel instability switches from bed degradation to rapid widening.

As we have shown above, the banks of the lower Deep Creek system are formed in cohesive material. Cohesion is either intrinsic, due to the presence of silt and clay fractions, or apparent, due to capillary suction or the binding effects of roots. Cohesive banks are often eroded by mass failure under gravity, during discrete events, when a critical stability condition is exceeded. The shape and extent of mass failures are controlled by the geometry of the bank section, the geotechnical properties of the bank material and the type and density of vegetation (Abernethy and Rutherfurd, 2000). Most mass failure sites that we observed on the banks of the Goulburn River appeared to have been the subject of circular failure mechanisms. That is, the failure plane describes a circular arc that intersects the bank face and the bank top.

Theories of slope stability state that a bank will collapse under its own weight if, for any assumed failure mechanism, the stress exerted by the weight of the bank material exceeds the internal strength of the bank material to resist that stress. The stability of a bank section is usually evaluated to determine its factor of safety ($F_s$), with respect to mass failure, by limit equilibrium techniques. The critical condition is considered to be that point where the soil mass is on the verge of failure and the shear strength of the soil is fully developed along a potential slip surface. The safety of the bank is generally expressed as the ratio of the stresses resisting failure to the stresses required to bring the bank into a state of limiting equilibrium along a given failure surface:

$$F_s = \frac{s}{\tau} \qquad (2)$$

where $s$ is the shear strength of the soil and $\tau$ is the shear stress acting along the failure surface. The driving stresses result from the downslope component of weight of the bank material. A safety factor of one would indicate imminent or incipient failure. In its simplest form the shear strength of a soil is described by the Mohr-Coulomb equation:

$$s = c + \sigma \tan\phi \qquad (3)$$

where $c$ is the soil cohesion, $\sigma$ is the total stress normal to the shear plane and $\tan\phi$ is the coefficient of internal friction.

During our field survey, we collected undisturbed samples from each our test sites on Deep Creek. From these we determined the saturated bulk unit weight ($\gamma$) and the shear strength parameters of $c$ and $\phi$. Shear strength parameters were determined by rapid, undrained triaxial compression tests. Such tests are a simple way to derive soil-strength values in the laboratory but they do not account for pore water pressures. During bank failure, there is often insufficient time for pore water drainage at the failure surface because the material is relatively impermeable and the failure plane is located some distance from the bank surface. To keep the analysis simple, we assume that all changes in bank material stress, during failure, are rapid and do not require effective stress analysis that includes consideration of pore water drainage.

Because of the large variability in bank stratification within and between reaches, we have made no attempt to account for variations in geotechnical parameters through the bank profile and have assumed that the bank material can be represented as a homogenous mass. From our laboratory results $c$ = 12.5 kPa, $\phi$ = 24° and $\gamma$ = 18.3 kN/m$^3$. (Note that these values represent the worst-case scenario of prolonged wet periods, when banks are likely to be at their least stable.) By equating the external and internal energies at failure, critical bank geometry combinations (where $F_s$ = 1) can be calculated for circular failures for known geotechnical properties of the bank materials (Figure 4.3).

Setting the geotechnical properties as above, we used Figure 4.3 to calculate critical geometries for a range of bank height/angle combinations (Figure 4.4). Against this stability curve we also plotted a range of bank sections (either observed in the field, or measured from previously surveyed cross-sections[2]. Bank data plotting below and left of the stability curve shown in Figure 4.4 are predicted as stable with respect to mass failure, while any above and right are predicted as unstable. For bank sections that plot in the stable region to become unstable, an increase in bank height, through bed degradation, or an increase in bank slope, through lateral toe erosion, must occur.

[2] See “Sheepwash, Skeleton, and Deep Creeks cross-section and longitudinal section comparison Lidar (2002) versus historic data (1982) Sheet 7/7” prepared by LICS for GBCMA.

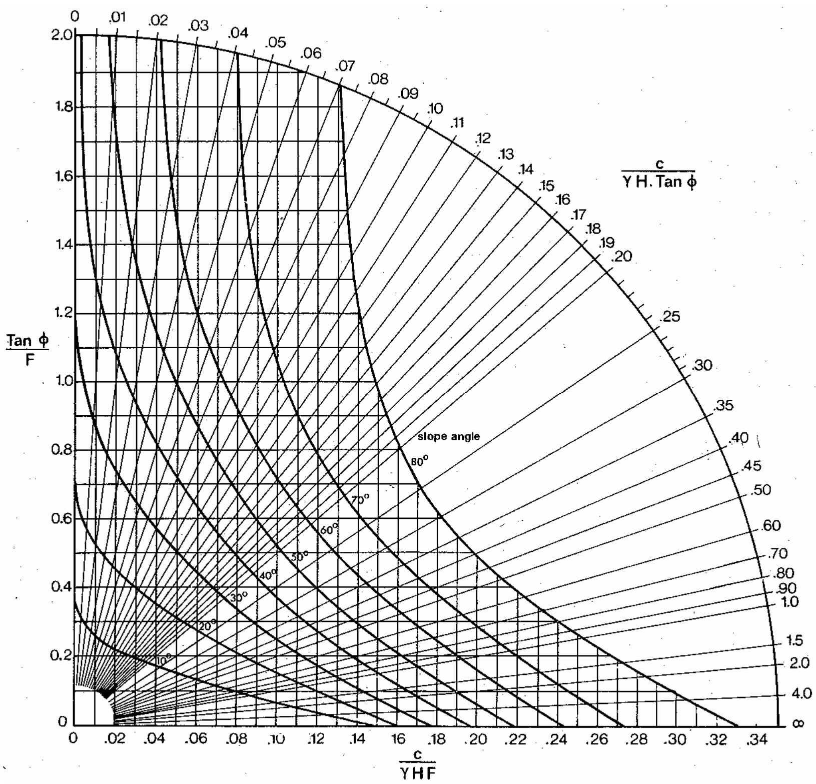



**Figure 4.3: Circular failure chart (Hoek and Bray, 1981 p. 238)**

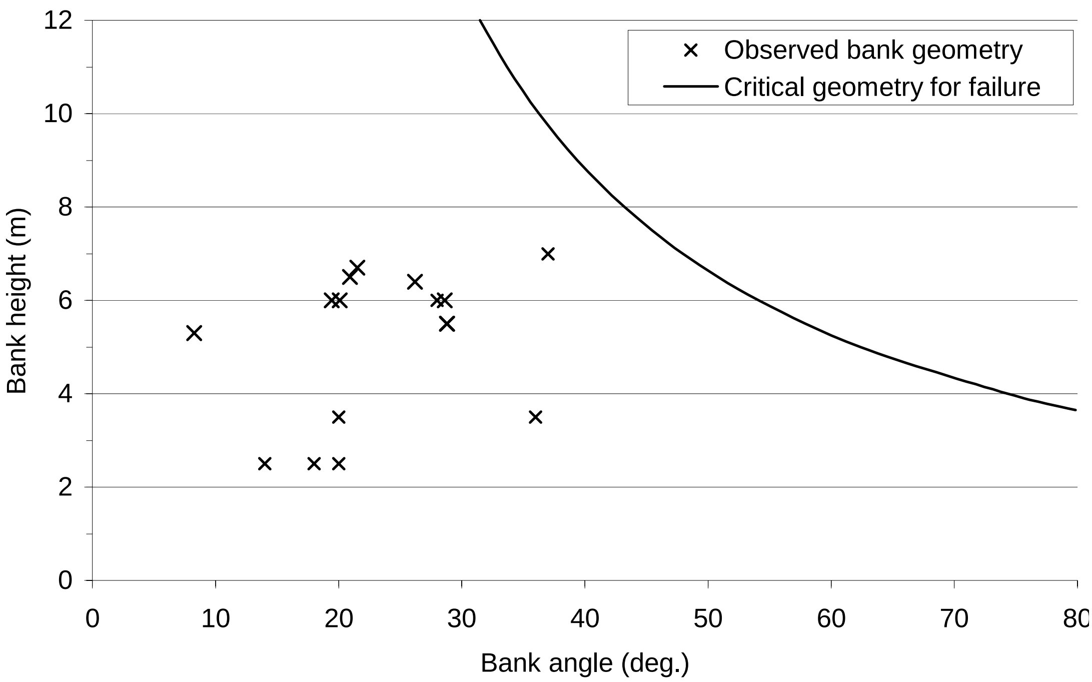



**Figure 4.4: Bank geometry of the Deep Creek system compared to critical conditions.**

To consider the effect of roots on bank mass-stability we need to introduce a parameter that describes the additional strength derived from root reinforcement. That is, a parameter that will increase the shear resistance of the bank material directly with root concentration. Coppin and Richards (1990) assert that the mechanical effect of roots is to enhance the confining stress and resistance to sliding of the soil mass. Due to the random orientation of roots within the bank the value of $\phi$ will remain unchanged and any increase in shear resistance can be allocated in Equation (3) to an increase in $c$. Abernethy and Rutherfurd (1998) showed that the effect of adding tree roots to bank profiles was to move the stability curve shown in Figure 4.4 up and to the right. Hence, all vegetated bank sections are even more stable than indicated by Figure 4.4.

The results presented in Figure 4.4 support our field observations very well. We did not observe any mass failures on the Deep Creek system. We did, however, observe a number of failure sites on the Goulburn River where failures had developed on high steep banks that were usually devoid of vegetation. Bailey and Rutherfurd (2005) presented results that show the boundary sediments of the Goulburn River are similar to Deep Creek. Hence, any deepening of lower Deep Creek that produces bank heights similar to the lower Goulburn would give rise to a proliferation of mass failure along the Deep Creek system.

# 5. Discussion

The levee system built along the lower Goulburn River has altered the partitioning of flows between the river channel and floodplain, and also the routing of flood flows on the floodplain. As a consequence, the spatial distribution of geomorphological processes (e.g. erosion) has been effected. Natural overflows from the Goulburn River into the distributary channels no longer occurs except where specific provision for outflow has been retained in some of the regulator structures. In effect the distributary channels have been robbed of their irregular water supply from the Goulburn River. Removing the levees would allow flood flows to dissipate into the upper Deep Creek floodplain.

Under natural conditions the most likely new course for an avulsion to the north would be into the Deep Creek system which is the deepest distributary channel. To the south, the most likely course is Wells Creek which joins the Goulburn at McCoys Bridge (Erskine *et al.*, 1993). The existing creeks (Bunbartha, Deep, Skeleton and Sheepwash) provide good potential for floodways from the Goulburn River as they provide flow capacity and a low flow channel.

Field investigations of the Deep Creek system revealed a large and complex avulsion system. Exposed tree roots in the lower sections of Deep Creek indicate local scour is occurring. Nickpoints were observed at numerous locations throughout the system, often at or near confluences with other creeks or channels. For example; a nickpoint is located at the confluence of Skeleton and Sheepwash Creeks with a 1 m drop in bed level (into Skeleton Creek). At another confluence (Deep Creek and an unnamed anabranch to the south) it was noted that the channel of the unnamed anabranch was perched some 4 m above the invert of Deep Creek. The face of the steep transition from the unnamed anabranch to Deep Creek suggests relatively recent, and possibly ongoing, erosion.

The most upstream end of Sheepwash Creek is characterised by a wide paleochannel with minimal incision, small localised erosion and large ancient trees. The upstream section of Skeleton Creek is characterised by palaeo pools and separated by sections with higher bed levels. These characteristics indicate that the erosion heads have not yet reached these sections of the respective creeks. This may be caused by the reduction of flows through these creeks in recent history.

There is a gradual downstream increase in the width and depth throughout the Deep Creek system and hence the cross-sectional area. Consequently, there is an increase in conveyance and potential for erosion in these channels, summarised under the following general types:

1) transitions from floodplain to defined channel;
2) gradual widening and deepening of the channel in a downstream direction;
3) rapid change in bed elevation at an erosion head; and
4) relatively rapid change in depth and width at confluences.

Points of rapid change in cross-sectional area represent potential sites of future erosion. As shown in the hydraulic scour analysis, above, average conditions in the channel do not give rise to widespread erosion. However, localised steep bed-sections will propagate relatively steep hydraulic grades and high velocities that may well prove erosive and cause further headward migration of the nickpoint. That we have observed nickpoints just above confluences implies that discharges in the upstream channel are not sufficient to maintain an active nickpoint under the current flow regime.

Under the proposed scheme flows up to (about) the 35 year annual recurrence interval (ARI) will spill onto the floodplain more often and for longer durations (Water Technology, 2005). The changed floodplain hydrology will give rise to changed flow conditions in Deep Creek. More frequent longer duration flows at potential erosion points in the system may rejuvenate the erosion nickpoints in the system. The following pages contain model results for the difference in pre- and post-scheme velocities for the 5 year, 10 year, 35 year and 100 year ARI floods.

The modelling results indicate an increased velocity in the Deep Creek system for all scenarios. Of particular interest is the increase in in-channel velocities for the smaller more frequent floods (up to the 5 year ARI). Based on the work of Judd (2005) we can conclude that the peak rate and amount of erosion along Deep Creek will occur during frequent events. However, to determine the peak rate and quantum of erosion it is necessary to know the flow at which the peak erosion rate occurs at the sites of potential future erosion.

Since erosive forces increase with discharge to a maximum amount and then drop, it is possible that the proposal to put more water through the Deep Creek system could either increase or decrease erosion. It may even be possible to release more water down Deep Creek and reduce erosion rates on the avulsion channels. For floods that currently have a discharge equal to or greater than the discharge of the most erosive flow, releasing more water to increase this discharge may not pose a threat to the avulsion. Such an increase in discharge may actually reduce erosion rates. An increase in the frequency or duration of events with a discharge equal to or greater than the most erosive flow will increase erosion on the avulsion.

## 5.1 Further work

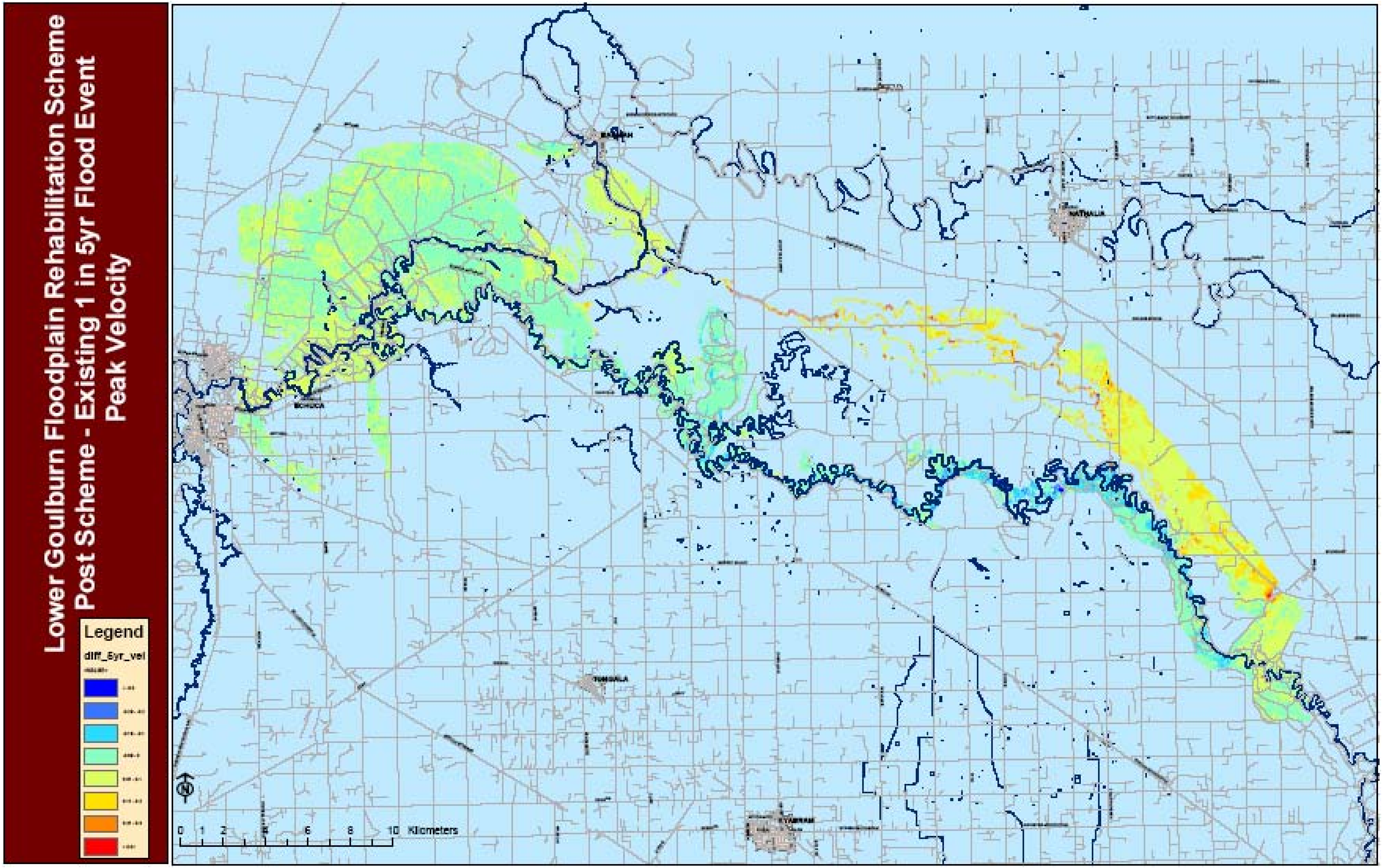
The recurrence interval at which the peak erosion rate occurs is dependant on the morphology and hydrology of the Goulburn River, the morphology of Deep Creek and the threshold of motion of floodplain materials along Deep Creek. The sampling and testing of floodplain materials, done to date, along with the floodplain hydraulic modelling provides a general picture of the system's erosion resistance and the effect of the scheme on the erosivity of flow. However, it has failed to specifically consider the adjustment of particular features in the system that may ultimately control the rate at which the avulsion will develop. Although we know that velocities will increase with the proposed scheme implementation, to manage the increase in flows down Deep Creek we need to know what the most effective or erosive flow is and how it varies across the sites that are being eroded.

The hydraulic modelling done to date has been concerned with understanding water levels during larger, relatively uniform flow events. Hence, the survey data for this hydraulic model consists of cross-sections kilometres apart. However, the flow properties describing erosion rates occur on features that are often only tens to hundreds of metres long; something that the existing survey data does not define adequately.

We recommend that part of the initial work in implementing the scheme will be to study these erosion features and design flow series that give the desired erosion outcome on Deep Creek. This study would consist of:

1) selecting a set of erosion features that are representative of the complexity of the Deep Creek system;
2) obtaining sufficient survey data to define the geometry of these erosion features;
3) development of finer-scale hydraulic models for the erosion features (tied to the backwater and hydrology of the larger Goulburn River model); and
4) determination of how shear stress on each erosion feature varies with discharge and thereby elucidation of the most erosive flow.

Of course, readers should be aware that all modelling (regardless of scale) can only be indicative of the future response of the system to changed flow conditions. Ultimately, the only test of the systems adjustment trajectory will be through monitoring of particular features under the new scheme. Avulsion development is very episodic. Any monitoring program would need to survive through a number of floods to adequately assess the stability or dynamism of potential erosion sites. At a minimum, monitoring should consist of repeat survey of the Deep Creek system one decade from the scheme’s inception. The completion of the avulsion cycle of the Deep Creek system could occur rapidly under both current and proposed hydrological conditions but we concur with Erskine *et al*. (1993) and Schumm *et al*. (1996) that avulsion is unlikely to happen within the next 100 hundred years.


Lower Goulburn Floodplain Rehabilitation Scheme
Post Scheme - Existing 1 in 5yr Flood Event
Peak Velocity
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diff_5yr_vel
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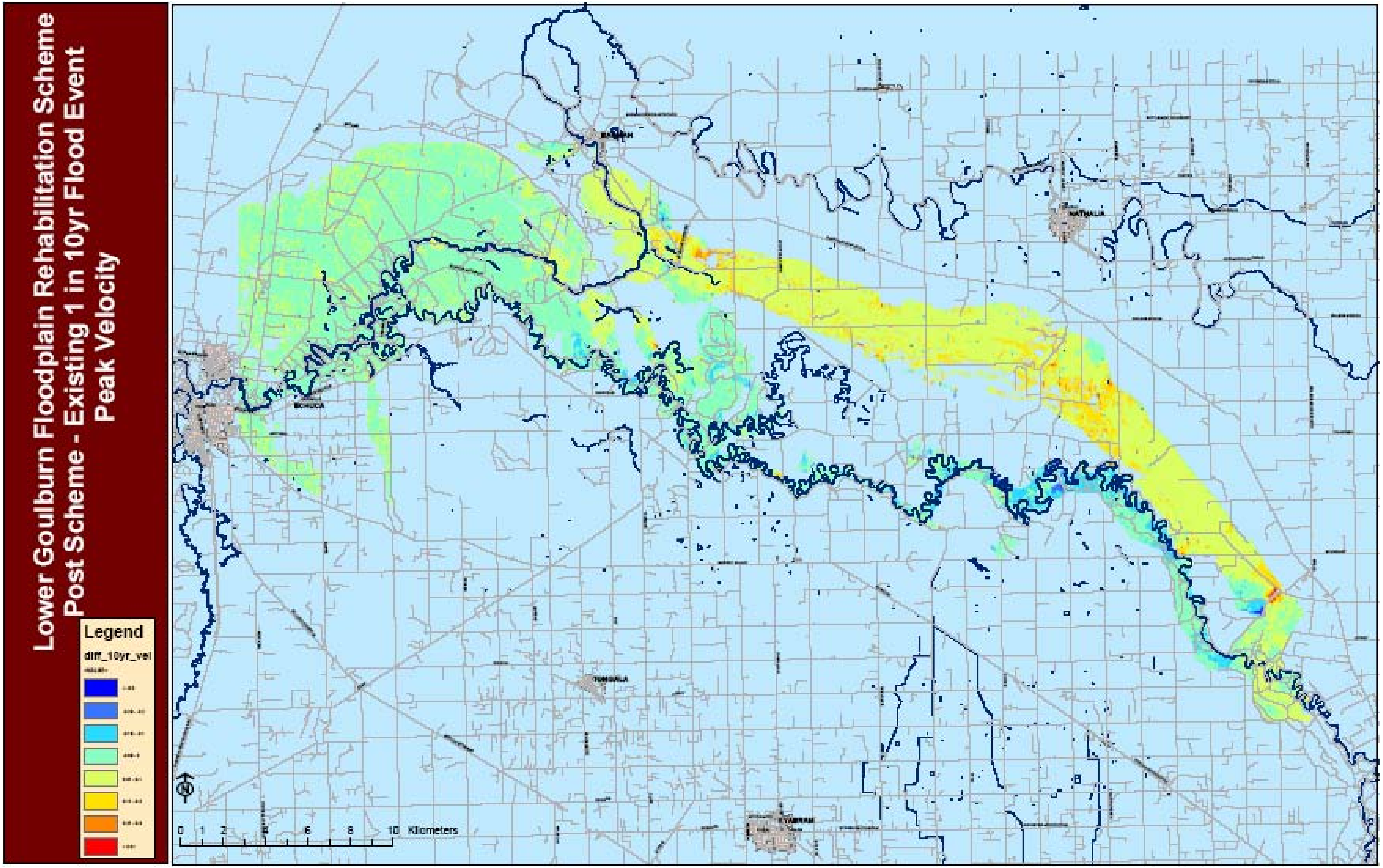
Lower Goulburn Floodplain Rehabilitation Scheme
Post Scheme - Existing 1 in 10yr Flood Event
Peak Velocity
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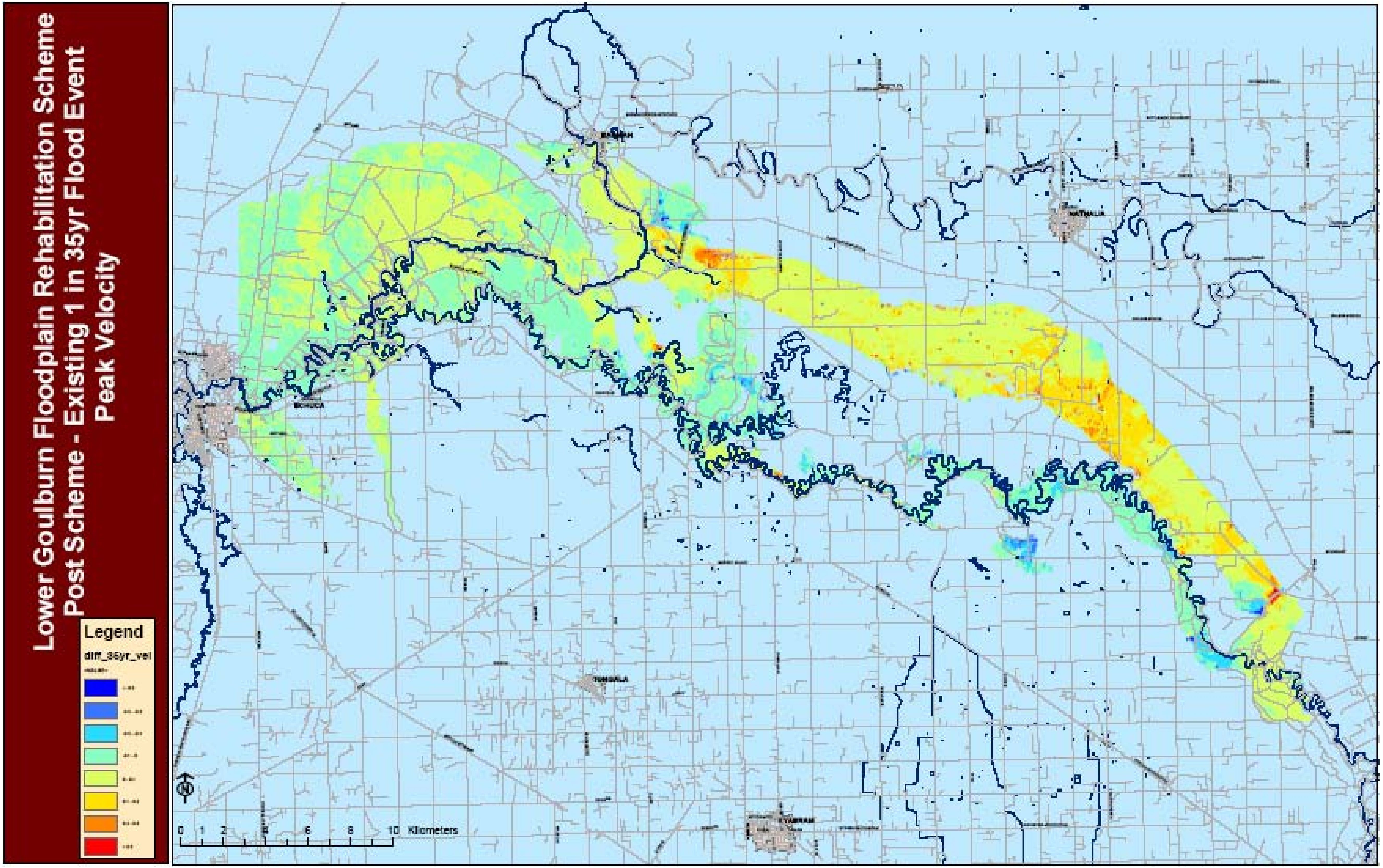
Lower Goulburn Floodplain Rehabilitation Scheme
Post Scheme - Existing 1 in 35yr Flood Event
Peak Velocity
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diff_35yr_vel
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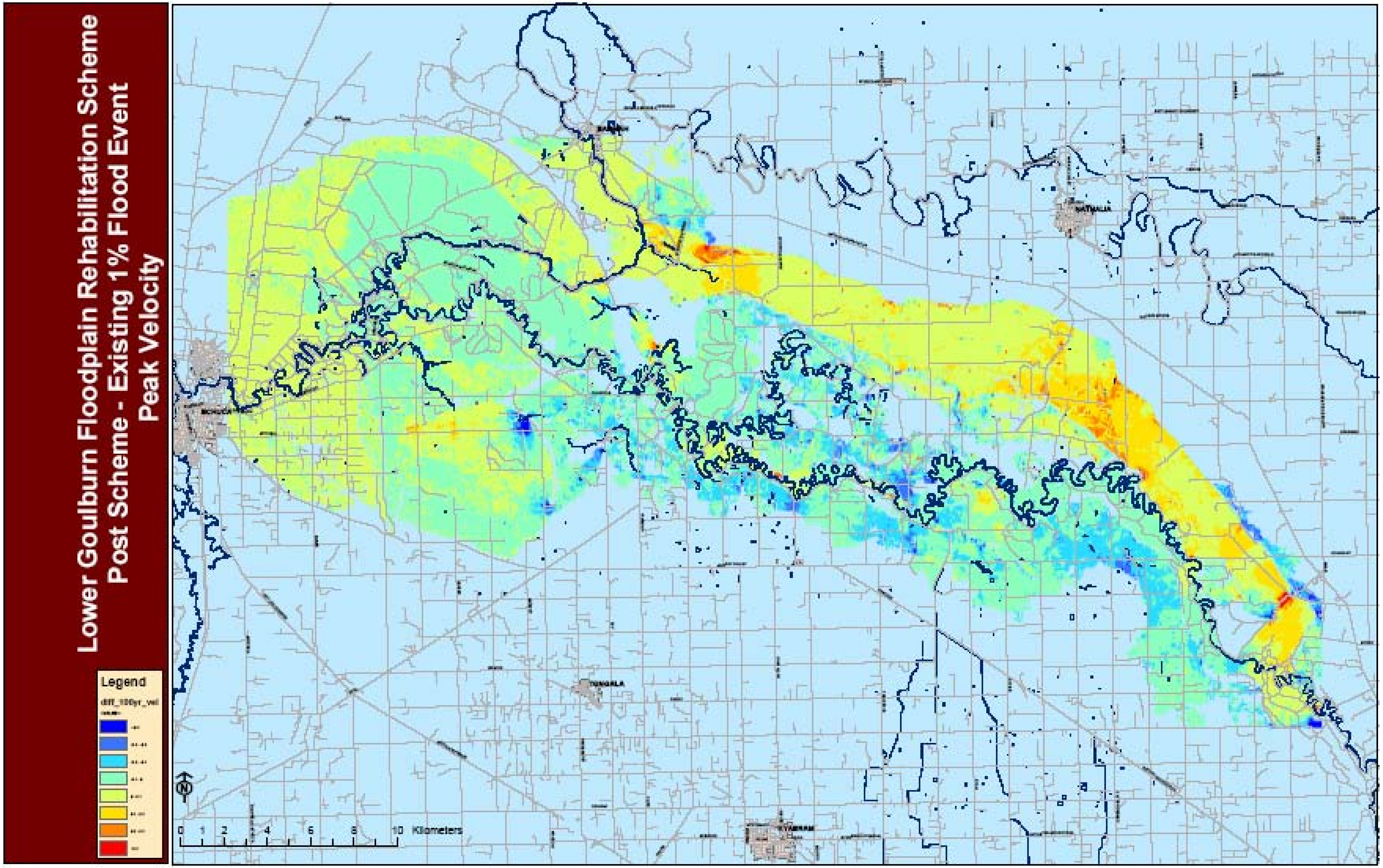
Lower Goulburn Floodplain Rehabilitation Scheme
Post Scheme - Existing 1% Flood Event
Peak Velocity
Legend
0 1 2 4 6 8 10 Kilometers

# 6. Conclusions

Instigation of the rehabilitation scheme would allow a return to a more natural long term flow regime for the lower Goulburn River and Deep Creek. Further, the release of flows to Deep Creek would potentially result in reduced flow rates in the lower Goulburn River downstream from Loch Garry. This would eventually prevent further instabilities, scour and erosion from occurring at some of the outlet structures (e.g. Hancocks) and in sections of Tessies Creek, You You Creek and Deep Creek. These short streams convey floodwaters north to the Murray River via Deep Creek.

Changes to the course of the Goulburn River across the Riverine Plain will continue. Diminishing downstream channel capacity, eroding floodpaths and distributary creeks potentially encourage the development of alternative courses capable of diverting the river by avulsion. This risk is increased if the ground surface is exposed by clearing or vehicle damage, or if flood flows are concentrated as a result of drainage or flood mitigation works.

Further work could assist in the prediction of channel stability under changed flow conditions but ultimately channel change occurs in response to an interacting array of complex processes, many of which cannot be predicted with any accuracy. The proposed scheme is, by its very nature, a large experiment in floodplain management. As such, managers should expect, and be prepared to react to, adverse outcomes from the changed regime. Avulsions do not occur rapidly (in human timescales, at any rate) and ongoing monitoring of the avulsion system will prove essential for assessing the impacts of the changed flow conditions. At the very least, repeat surveys of the channel system will provide a picture of rate and nature of evolution of the Goulburn River's lower floodplain. Timely appreciation of adjustment trends will allow managers to adaptively manage the frequency and duration of floodflows on the floodplain and the Deep Creek system's response to those flows.

Prevention of avulsions are generally not found to be feasible, even on streams which are much smaller than the lower Goulburn. And, while channel evolution occurs on a time frame that can be measured in thousands of years, the time necessary for an avulsion cycle to occur is highly variable. The occurrence of the next avulsion in the lower Goulburn River is unlikely to happen within the next 100 hundred years.

# 7. References


Abernethy, B. and I.D. Rutherfurd, 1998. Where along a river's length will vegetation most effectively stabilise stream banks? *Geomorphology*, 23(1): 55-75.

Abernethy, B. and I.D. Rutherfurd, 2000. The effect of riparian tree roots on the mass-stability of riverbanks. *Earth Surface Processes and Landforms*, 25(9): 921-37.

Allen, P.M., J. Arnold and E. Jakubowski, 1999. Prediction of stream channel erosion potential. *Environmental and Engineering Geoscience*, 5(3): 339-51.

Bailey, C. and I. Rutherfurd, 2005. The complex effects of fine tree roots on shear stress of cohesive stream banks. In I.D. Rutherfurd, I. Wiszniewski, M.J. Askey-Doran and R. Glazik (eds.), *Proceedings of the Fourth Australian Stream Management Conference: Linking Rivers to Landscapes, Launceston*. Department of Primary Industries, Water and Environment, Hobart: 52-8.

Bailey, C. and I. Rutherfurd, in prep. Do the roots of riparian trees have a major effect on scour of cohesive riverbanks?

Bailey, C., I. Rutherfurd and J. Grove, in prep. Four-stage conceptual model of fluvial scour on root-embedded cohesive riverbanks.

Blaisdell, F.W., C.L. Anderson and G.G. Hebaus, 1981. Ultimate dimensions of local scour. *Journal of the Hydraulics Division, Proceedings of the ASCE*, 107(HY3): 327-37.

Bowler, J.M., 1976. Quaternary climate and tectonics in the evolution of the Riverine Plain, southeastern Australia. In J.L. Davies and M.A.J. Williams (eds.), *Landform Evolution in Australasia*. Australian National University Press, Canberra: 70-112.

Butler, B.E., G. Blackburn, J.M. Bowler, C.R. Lawrence, J.W. Newell and S. Pels, 1973. *A Geomorphic Map of the Riverine Plain of Southeastern Australia*. Australian National University Press, Canberra.

Cameron McNamara, 1987. *Lower Goulburn Flood Plain Management Study: Shepparton to Kanyapella*. Main Report. Rural Water Commission of Victoria, Melbourne.

Coppin, N.J. and I.G. Richards, 1990. *Use of Vegetation in Civil Engineering*. Construction Industry Research and Information Association / Butterworths, London.

Erskine, W.D., I.D. Rutherfurd, A.R. Ladson and J.W. Tilleard, 1993. *Fluvial Geomorphology of the Goulburn River Basin*. Ian Drummond and Associates for the Mid-Goulburn Catchment Coordinating Group, Strathbogie.

Hanson, G.J., 1991. Development of a jet index to characterise erosion resistance of soils in earthen spillways. *Transactions of the American Society of Agricultural Engineers*, 34(5): 2015-20.

Hanson, G.L., A. Simon and K.R. Cook, 2002. Non-vertical jet testing of cohesive streambank materials. In *ASAE Annual International Meeting/CIGR XV World Congress, Chicago*.

Hoek, E. and J. Bray, 1981. *Rock Slope Engineering* (Third Edition). The Institution of Mining and Metallurgy, London.

Judd, D.A., 2005. *How a river anabranch forms: a process study on the Riverine Plain of south-eastern Australia*. PhD Thesis, Monash University, Melbourne.

Lawler, D.M., 1992. Process dominance in bank erosion systems. In P. Carling and G.E. Petts (eds.), *Lowland Floodplain Rivers*. Wiley, Chichester: 117-43.

Schumm, S.A., W.D. Erskine and J.W. Tilleard, 1996. Morphology, hydrology, and evolution of the anastomosing Ovens and King Rivers, Victoria, Australia. *Geological Society of America Bulletin*, 108(10): 1212-24.

SKM, 1998. *Lower Goulburn Waterway and Floodplain Management Plan*. Sinclair Knight Merz for the Goulburn-Broken Catchment Management Authority, Shepparton.

Thoms, M., P. Suter, J. Roberts, J. Koehn, G. Jones, T. Hillman and A. Close, 1998. *Report of the River Murray Scientific Panel on Environmental Flows: Dartmouth to Wellington and the Lower Darling River*. Murray-Darling Basin Commission, Canberra.

Thorne, C.R., 1991. Bank erosion and meander migration of the Red and Mississippi Rivers, USA. In *Hydrology for the Water Management of Large River Basins: 20th General Assembly of the International Union of Geodesy and Geophysics, Vienna*. International Association of Hydrological Sciences: 301-13.

Tilleard, J.W., 2001. *River channel adjustment to hydrologic change*. PhD Thesis. Department of Civil and Environmental Engineering, University of Melbourne, Melbourne.

Water Technology, 2005. *Lower Goulburn Floodplain Rehabilitation Scheme: Hydraulic Modelling Report*. Report No. J018/R5 Draft A. Report to the Goulburn Broken Catchment Management Authority, Melbourne.

Wynn, T., 2004. *The Effects of Vegetation on Stream Bank Erosion*. Ph D Thesis. Virginia Polytechnic Institute and University.

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# Appendix A Particle size analysis

Particle size analysis was conducted on five samples collected from three sites on the Deep Creek system (Table A.1, Table A.2). Samples were won from the bank toe (denoted by T in the tables) and the bank face (denoted by B in the tables) at the lower Deep Creek sites and from the bed/toe at the Skeleton Creek site.

Site one consists of a relatively straight section of Deep Creek characterised by a trapezoidal cross section approximately 35 m wide (at bankfull) by 8 m deep. The bed width at this site was approximately 20 m. The site has exposed tree roots implying some local scour may be occurring, however no mass failures or signs of intensive scour were observed. Sediments at the site fined upwards through the bank profile.

Site two had the same trapezoidal shape as site one, although the banks were not as high and the bankfull width was 42 m. The bed width was marginally less at this site. There were less exposed tree roots at site two possibly implying a slightly more stable site. The sediment at site two contained more clay content than site one, and fined up the bank.

Site three was located further upstream on Skeleton Creek near McLellands Road. This site was characterised by discontinuous channel morphology approximately 35 m wide by 2.5 m deep transitioning to 1 – 2 m channels of the same width between the deeper sections. The mature River Red Gums at this site showed minor scouring around the roots.

**Table A.1: Particle size distribution.**

| Particle size (mm) | Percent passing | | | | |
|---|---|---|---|---|---|
| | Skeleton | Deep 1T | Deep 1B | Deep 2T | Deep 2B |
| 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 75.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 53.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 37.5 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 26.5 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 19.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 13.2 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 9.5 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 6.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 4.75 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 2.36 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1.18 | 97.4 | 100.0 | 99.8 | 99.9 | 99.9 |
| 0.600 | 94.9 | 99.9 | 99.1 | 99.7 | 99.7 |
| 0.425 | 93.7 | 99.1 | 98.0 | 99.5 | 99.5 |
| 0.300 | 91.7 | 89.8 | 94.0 | 99.1 | 99.1 |

/cont.

**Table A.1 (cont.): Particle size distribution.**

| Particle size (mm) | Percent passing | | | | |
|---|---|---|---|---|---|
| | Skeleton | Deep 1T | Deep 1B | Deep 2T | Deep 2B |
| 0.150 | 83.9 | 54.5 | 66.4 | 92.8 | 92.8 |
| 0.075 | 78.3 | 41.1 | 44.9 | 77.4 | 77.4 |
| 0.051 | 74.2 | 39.9 | 41.7 | 70.8 | 70.8 |
| 0.043 | 69.0 | 38.0 | 36.8 | 64.1 | 64.1 |
| 0.031 | 65.6 | 34.8 | 32.8 | 56.4 | 56.4 |
| 0.019 | 62.1 | 32.9 | 29.5 | 52.6 | 52.6 |
| 0.014 | 58.7 | 30.4 | 28.2 | 47.8 | 47.8 |
| 0.010 | 55.2 | 28.5 | 27.0 | 44.4 | 44.4 |
| 0.0075 | 52.2 | 26.9 | 25.4 | 42.3 | 42.3 |
| 0.0053 | 50.0 | 25.3 | 24.1 | 39.2 | 39.2 |
| 0.0038 | 46.6 | 24.1 | 22.9 | 36.8 | 36.8 |
| 0.0028 | 42.5 | 22.5 | 20.9 | 34.5 | 34.5 |
| 0.0020 | 40.1 | 21.6 | 19.7 | 32.6 | 32.6 |
| 0.0012 | 36.4 | 19.9 | 17.3 | 28.9 | 28.9 |

**Table A.2: Sediment fractions (%).**

| Sediment | Skeleton | Deep 1T | Deep 1B | Deep 2T | Deep 2B |
|---|---|---|---|---|---|
| Gravel | 0.6 | 0.0 | 0.1 | 0.1 | 0.0 |
| Sand | 23.5 | 60.3 | 58.3 | 33.2 | 27.2 |
| Silt | 35.7 | 18.3 | 22.2 | 38.8 | 40.5 |
| Clay | 40.2 | 21.4 | 19.4 | 27.9 | 32.3 |