Review of floodplain mining and risks

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Contents

Executive Summary

Floodplain mining impacts

Major floodplain mining impacts can occur if, during flooding, the stream creates a new channel through the pit. If pit capture occurs, physical impacts include bed degradation and aggradation, bank erosion and channel widening, with these physical impacts often extending many kilometres away from the pit. Infrastructure such as road crossings and services that lie within the area of physical impact may also be damaged or destroyed.

Risk associated with floodplain mining

Three main risk scenarios have been identified that have the potential to result in a pit capture. These are:

- Lateral migration of river channel into the pit
- Sub-surface piping into pits and subsequent failure of pit walls
- Flow of water into and through the pit

Variables that influence likelihood and consequence

The likelihood of pit capture is a function of a number of variables. Hydrology is a key variable, as it is the flow of water into a pit from the river that ultimately leads to its capture. Local hydraulic effects are also important such as the flow velocity adjacent to erodible floodplain and bank material. Other variables important are the proximity of the pit to a waterway and the depth of the pit relative to the channel. Pits in close proximity to a waterway and where extraction has continued to a depth lower than the thalweg of the adjacent waterway will pose a greater risk than pits that are positioned further away from the waterway where extraction does not extend below the level of the thalweg.

The consequences of a pit capture depends on the relative scale of the mining operations and the river and the infrastructure that is located in the impact area. The larger and deeper the captured pit, the greater the potential change is to the river. The physical process of pit capture have been well documented from case studies, incision upstream and downstream of the pit are expected, with bed adjustments continuing until the river establishes a new equilibrium and grade. Any infrastructure which traverses the impacted area is at risk of being damaged during this period of adjustment.

Management strategies to address risks

Not mining on the active floodplain and restricting operations to terraces and upland areas is an effective way of mitigating the risk of pit capture. Choosing to mine only in inactive floodplain areas, i.e. those that lie above the 100-yr flood, or areas determined as disconnected from the river through historical channel migration analysis also reduces the risks. Technical guidelines exist that provide advice on the design and location of floodplain pits to ensure that sand and gravel extraction is carried out in a sustainable manner and that the function of the floodplain, flood control features and infrastructure is not compromised.

The guidelines and criteria that have been set regarding the depth of extraction is based on recognition that avulsion risk is increased where the depth of the pit extends below the level of the adjacent waterway and that pits that lie closer to the waterway are more susceptible to capture than those positioned further away. This should not be used to support deeper extractions further away from a waterway. The likelihood of capture is lower than being positioned right next to a waterway but probably still inevitable in a long duration flood. The geomorphic consequences are also greater with the avulsion of a longer length of waterway.

Floodplain mining in the Goulburn Valley

Pit capture and associated changes in channel alignment are an acknowledged risk in the Goulburn Valley. The scale of the current and historic operations and their positioning relative to the river and key infrastructure indicate that significant physical and infrastructure impacts could occur. In the next stage of this study we will complete a series of desktop and field based risk assessments to evaluate the severity of these risks.

1. Introduction

1.1 Context

The Goulburn Broken Catchment Management Authority (CMA) in association with the Department of Land, Water and Planning (DELWP) has commissioned a study into the sustainability of sand and gravel extraction from the valley of the Goulburn River. The output of this study is to provide a planning framework for sustainable extraction, and to identify legacy issues and treatments associated with existing and abandoned extraction operations.

1.2 Study objectives

The objectives of the study as set out by Goulburn Broken CMA are to inform agencies of:

- The sustainable scale and location of gravel extraction in the Goulburn Valley
- The risks associated with legacy issues at existing and abandoned sand and gravel pits

In addition, the study will develop a planning framework to ensure sustainable mining. This is likely to involve planning scheme amendments to the Strathbogie, Mitchell and Murrindindi Planning Schemes to assist decision making about sand and gravel extraction in the Goulburn Valley.

This report is the second of two reviews, undertaken early in the study:

1) Review of planning schemes across Victoria to understand how they address/manage quarries
2) Review of technical literature that documents the impacts of floodplain mining on river systems

The outcomes of these two reviews will contribute to the development of the planning framework and tools that assist with making decisions around the limits of sand and gravel extraction in the Goulburn Valley.

1.3 Outline of this review

A large body of research exists that documents the impacts of floodplain mining on river systems. This literature is reviewed with a focus on identifying the range of potential impacts and risks associated with the industry on the river and infrastructure. The review also documents the different methods used to prevent or limit floodplain mining impacts.

Section 2 provides a brief description of sand and gravel mining operations in river systems, with the focus of this review being on those operations that occur on floodplains and the potential for these to impact on the stability of the river system. Documented case studies are reviewed from around the world to demonstrate the range of physical and infrastructure impacts of floodplain mining.

Section 3 describes the three main risks scenarios that have the potential to result in pit capture, which is of greatest concern to this study. This is followed by an analysis of the variables and factors that influence the likelihood of each risk scenario and potential consequences should either of the three risk scenarios be realised.

Section 4 documents the outcomes of a review of methods that have been adopted around the world to prevent or limit floodplain mining impacts on the river or infrastructure. Limits or criteria that have been placed on the design and location of extraction pits to lower the likelihood and consequences associated with different risks and prevent adverse impacts are also documented.

Section 5 provides an overview of sand and gravel extraction operations in the Goulburn Valley, concerns and issues.

A summary of the outcomes of the report and next steps in the study is provided in **Section 6**.

2. Sand and gravel mining in river systems

2.1 Types of mining and impacts

Sand and gravel are used as construction aggregate for roads and highways (base material and asphalt), pipelines (bedding), septic systems (drainage in leach fields), and concrete (aggregate mix) for highways and buildings, as well as a range of other uses (i.e. garden landscaping). In many areas, sand and gravel are derived primarily from alluvial deposits as shown in Figure 2.1, either from pits in river floodplains and terraces, or by in-channel (instream) mining removing material with heavy equipment (Kondolf, 1997; Ladson & Tilleard, 2013; Langer, 2003).

In very general terms, a specified volume of sand and gravel extractions will have less impacts to the river and hydrologic processes the higher up in the landscape the extraction is located (Langer, 2003). Sand and gravel extractions from floodplain areas are generally considered preferable to removing sand from stream channels. Extracting sand and gravel from terraces is generally preferable to extracting sand and gravel from floodplains (Langer, 2003).

In-stream mining modifies channel characteristics, especially where material is removed at a greater rate than it can replenish. Removal of material changes the cross section and may increase the gradient of the channel at the site of excavation, leading to upstream incision. Removing material can also result in a decrease in bedload, and lead to downstream incision. The course of the stream may change, causing bank erosion and undercutting of structures crossing the channel and floodplain (Langer, 2003).

Floodplain extraction is viewed as more preferable as it does not directly remove material from the in-stream environment. However, major impacts from floodplain extraction may occur if, during flooding, the stream leaves its channel and creates a new channel (referred to as an avulsion) through the pit (referred to as pit capture). After pit capture the stream will deposit its bedload in the pit, which may result in downstream erosion. The upstream end of the pit is also a knickpoint in the bed profile, and this knickpoint typically migrates upstream, inducing incision upstream of the pit as well.

Extraction of material from terraces is viewed as preferable to extraction on floodplains, as the terraces are infrequently inundated by floods. The potential for the stream to leave its channel and create a new channel though a terrace pit is low. Pit capture, could, however still occur in the situation where the bottom of the pit lies below the level of the floodplain and the stream erodes laterally or there is failure of pit walls. The outcome of both situations is the potential for a new channel to avulse into the pit, similar to that which would occur on lower floodplain areas.

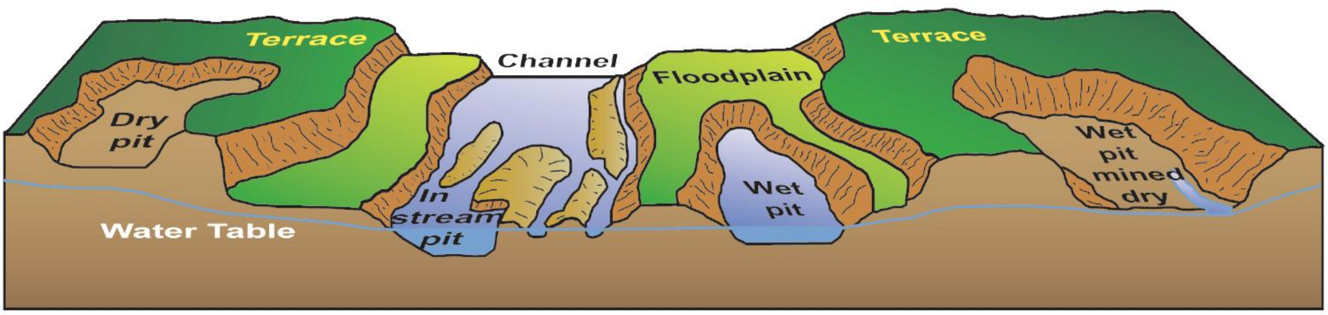

Figure 2.1 : Diagram highlighting that extraction may occur in different areas along a valley (Langer, 2003).

2.2 Overview of impacts of floodplain mining

Table 2.1 provides an overview of some of the potential impacts caused by floodplain pit capture. Pit capture impacts on a rivers geomorphic characteristics, sediment transport, hydraulics, hydrology, water quality and aquatic habitat, with these impacts extending upstream and downstream of the pit as well as the area of the pit itself.

Table 2.1 : Summary of potential impacts caused by floodplain pit capture (after Bureau of Reclamation, 2005).

Elements of Avulsion	**Nature of Impact**		
	Upstream	**Local**	**Downstream**
Geomorphic characteristics	· Incision of channel · Increased gradient · Coarsening of bed · Undercutting and erosion of banks · +/- lateral migration rates	· Alluvial fan development · Reshaping of pits · Loss of natural channel geometry · Increased open water area	· Increased lateral migration · Increased channel width · Incision
Sediment transport	· Increased sediment transport capacity · Reduction in bed load deposition	· Deposition of sediment in pits · Short-term increase in turbidity · Erosion of gravel pit banks	· Reduced sediment supply · Erosion of bed · Coarsening of bed · Increased bank erosion · Short term increase in fine sediment supply
Hydraulics	· Increased slope · Increased velocities · Decreased normal depth · Increased bed roughness	· Decreased slope · Increased channel depth · Increased channel width · Reduced bed roughness	· Increased bed roughness
Hydrology		· Increased flood storage · Increased evaporation · Altered groundwater flow patterns	· Reduction of flood levels · Attenuation of flood peaks · Changes in summer low flows · Lower riparian groundwater levels due to bed lowering
Water Quality		· Temperature increase · Short-term increase in turbidity · Alteration of hyporheic zone	· Temperature increase · Short-term increase in turbidity
Aquatic Habitat	· Habitat disruption or loss due to channel incision · Potential conversion of habitat type/quality · Short and long term habitat instability	· Conversion of free flowing habitat to still water habitat · Potential capture of fish following floods · Potential release of non-native species from captured pit(s) · Alteration of hyporheic zone · Short and long term habitat instability	· Habitat disruption or loss due to erosion of bed · Habitat loss due to altered sediment supply · Potential conversion habitat type/quality · Short and long term habitat instability

2.3 Case studies of physical and infrastructure impacts

Significant physical and infrastructure impacts can arise as a result from river channel changes caused by floodplain mining, as shown through a review of local, national and international case studies. A brief summary of these impacts is presented in Table 2.2. Physical impacts include bed degradation and aggradation, bank erosion and channel widening, with these physical impacts often extending many kilometres away from the pit. Infrastructure such as road crossings and any services (i.e. electricity, telecommunication, water, gas, sewer) traversing the floodplain can be damaged or destroyed, with financial damages in the hundreds of thousands to millions of dollars.

Table 2.2 : Documented physical and infrastructure impacts resulting from river channel changes caused by floodplain mining.

River	Physical Impacts	Infrastructure Impacts	Reference
Goulburn River, Victoria, Australia	Capture of Island Creek tributary (piping failure of bank) caused a knickpoint to progress upstream 150 m, substantial bank collapse and widening, toppled multiple mature red gums (Figure 2.2)	Destroyed a road crossing (Figure 2.2)	Craigie (2012)
Georges River, Western Sydney, Australia	Many gravel pits have been captured by the river, increasing tidal velocities and causing channel erosion		Warner and Mclean (1977)
Fish River, Bathurst, Australia Nepean River, Castlereagh, Australia	Rivers changed course through gravel pits		Erskine (1990)
Tangipahoa River, Louisiana, USA	Six gravel mining pits located within 150 m of the channel, up to 15 m deep were captured by the river between 1980 and 2004. Up to 6 m of bed degradation occurred upstream of pit captures, with aggradation downstream because of increased erosion.	A highway bridge failed because of the bed degradation (Figure 2.3).	Mossa and Marks (2011)
Big Escambia Creek, Florida, USA	Avulsion through several pits shortened the length and shifted the creeks junction with the Ecambia River 1.2 km upstream	Damages led to a $7.7 million (USD) stream restoration project	U.S. Army Corps of Engineers Mobile District (2000)
Tujunga Wash, California, USA	Bed degradation of 4 m caused when floodwaters entered a gravel pit 15 to 23 m deep.	Failure of 3 highway bridges and destruction of 7 houses	Bull and Scott (1974)
San Benito River, California, USA	3 m of bed degradation and channel widening over 7.5 km	Loss of one bridge and damage to two others. City water and sewer mains required replacement. Damages estimated at $11 million (USD).	Harvey and Smith (1998)
Stony Creek, California, USA	Change in channel alignment with migration of meander bend into gravel pit	Caused local scour around bridge piers of Interstate Highway 5, necessitating repair	Kondolf and Swanson (1993)
Merced River, California, USA	River flows through at least 15 gravel pits, of which eight were excavated on the floodplain and subsequently captured by the channel	Funding has been allocated to fix breached levees on one gravel pit at a cost of US$361,000.	Kondolf (1997)
Washington Creek, Penny River, Nome River, upper Aufeis Creek, Skeetercake Creek, lower Middle Fork Koyukuk River and Phelan Creek, Alaska	12 of 25 floodplain gravel pits studied by the US Department of the Interior had resulted in flow diversion, or the high potential for diversion, through the pits. Physical consequence of diversion included development of braided channel characteristics along new channels and loss of flow in former channels.		Rundquist (1980)
Cowlitz River, Yakima River, East Fork River, East Fork Lewis River, Washington State, USA	Review showed that in the years 1984 and 1996, 11 floodplain gravel pits had captured river flow.		Norman et al. (1998)

River	Physical Impacts	Infrastructure Impacts	Reference
Rogue River, Oregon, USA	Floods progressively eroded the bank and flow entered the pit	Bank erosion progressed upstream onto a residential property and downstream to a powerline which was lost	Klingman (1998)
Clackamas River, Oregon, USA	High flows in 1996 led to the capture of an off-channel pit and resulted in 2 m of incision documented about 1 km upstream	Incision and bank erosion caused undermining of a building at the gravel mine site	Kondolf (1997)
Yakima River, Washington River, USA	River shifted course to flow through gravel pits near Yakima	Interstate highway threatened	Bureau of Reclamation (2005); Dunne and Leopold (1978)
South Platte River, Colorado, USA	1.2 m of be incision was caused between 1983 and 1986 by in-stream mining and the capture of a floodplain mining pit	Major work was required to protect a bridge, gas line and several large water mains. Damages estimated at $1.3 million (USD).	Stevens et al. (1990)
Blackwood Creek, California, USA	Pit capture led to upstream and downstream bed incision and an increase in sediment delivery to a downstream lake		Todd (1989)
Jarama River, Spain	Floodplain gravel mining caused the river to straighten because of diversion of the river through gravel pits		Uribelarrea et al. (2003)

A local example that demonstrates the impact that river channel changes caused by floodplain mining can have is provided by the capture of Island Creek in the Goulburn Valley. Island Creek is an anabranch of the Yea and Goulburn Rivers. In August 2010, the creek avulsed into a pit operated by Yea and Sand Gravel. The avulsion caused substantial incision and bank erosion along the creek, with an erosion knickpoint progressing 150 m upstream (Craigie, 2012). As this knickpoint progressed upstream the incision and bank erosion destroyed a recently constructed road crossing and riparian vegetation (Figure 2.2). The avulsion was caused by piping into the pit associated with creek flows that remained in the channel (Craigie, 2012; Goulburn Broken CMA, 2014).

There are many examples of floodplain mining leading to pit capture in the literature, with physical impacts leading to significant infrastructure damages. Particularly notable, is the damage and destruction of a highway bridge on the Tangipahoa River, USA (Mossa & Marks, 2011). Figure 2.3 shows a photograph of the highway bridge that failed on the Tangipahoa River.

Figure 2.2 : Diversion of Island Creek into a gravel pit on the Goulburn River floodplain (A) caused upstream bed and bank erosion (B) destroying bridge and toppling riparian trees (C). Source: Craigie (2012).

Figure 2.3 : Looking downstream to the bridge failure at State Highway 10 near Arcola along the Tangipahoa River in Louisiana, ISA. Mossa and Marks (2011) attribute this bridge failure to mining related degradation.

3. Risks associated with floodplain mining

3.1 Establishing the context

Floodplain mining increases the vulnerability of the landscape, especially during flood events (Mossa & Marks, 2011). Floodplain mining converts flood-prone riparian land (agricultural land or areas of native forest) into open pits with minimal vegetation which typically intersect the groundwater table (Kondolf, 1997). As material is removed from the floodplain, the topographic, hydrologic and geomorphic characteristics of the floodplain are changed. Changes to the surface topography on floodplains affect patterns of water flow and sediment transport. Low points and areas of low flow resistance are created into which water can flow into leading to pit capture and change in river alignment.

As shown through a review of case studies in the literature, the physical and infrastructure impacts associated with pit capture and change in river alignment can be significant. This chapter describes the three main risks scenarios that have the potential to result in pit capture, which is of greatest concern to this study. This is followed by an analysis of the variables and factors that influence the likelihood of each risk scenario and potential consequences should any of the three risk scenarios be realised.

3.2 Identification of risks

Based on a review of the literature, we have identified three main risk scenarios that have the potential to result in pit capture and a change in river alignment. These are:

- Lateral migration of river channel into the pit
- Sub-surface piping into pits and subsequent failure of pit walls
- Spill of water into and through the pit

The processes and mechanisms that trigger each of these risk scenarios are described in the following sections.

3.2.1 Lateral migration of river channel into the pit

Pit capture occurs when the strip of land separating the pit from the channel is breached by lateral channel erosion and migration of the channel into the pit (Kondolf, 1997). This is quite a common mechanism via which pit capture can occur.

3.2.2 Piping failure of pit walls

Piping failure is a risk particularly during high flow conditions where there are high water levels in the river and this leads to seepage of groundwater from the pit walls, and weakening of substrate resulting in erosion and failure of material. Piping failure was the cause of breaching at Island Creek.

3.2.3 Flow of floodwater into and through the pit

If floodwaters have access to pit areas, the pit will present an area of decreased flow resistance. This low resistance combined with the pit geometry, which often results in a shortened flow path for flood flows, will increase hydraulic conveyance, and lead to hydraulic drawdown and subsequent acceleration of flow towards the pit. These hydraulic conditions cause the sediment transport capacity of the flow to increase above the incoming rate of sediment supply, resulting in erosion (e.g. Galay, 1983). Local turbulent flow around obstructions such as trees on the bank of extraction pits could also initiate knickpoints that develop into avulsions (Gibling et al., 1998; Tooth & Nanson, 1999).

The above sediment transport discontinuity will persist whilst floodwaters are passing through the pit. If the water level in the pit is not at floodplain level at the start of a flood, the initiation of erosion may be augmented by supercritical flow and the associated hydraulic jump as floodwater cascades into the pit filling it with water. As this cascade of floodwater is a sediment transport discontinuity under different hydraulic conditions to those detailed above, and will not persist for long in the context of floods on the Goulburn River, it is not listed as a separate process.

3.3 Risk assessment

3.3.1 Likelihood

When considered in general terms, the indications from the literature are that pit capture is a highly likely outcome. Norman et al. (1998) writes "*In the long term, stream capture by gravel pits is a near certainty. Because the gravel pits have a lower base elevation, there is a risk of rapid channel change into the pits during high flows*". Kondolf (1997) concludes that "*In general, pit capture is inevitable for floodplain pits…*".

Table 3.1 lists the risk scenarios and key variables that influence the likelihood of each scenario occurring. A key variable that is a common influence on likelihood for the three risk scenarios is hydrology. The magnitude, frequency and duration of flows that fill the channel and inundate the floodplain drive the hydraulic and sediment transport processes that potentially result in pit capture. The proximity of the pit to the waterway is also common influence for the three risk scenarios.

Hydrology, proximity of the pit to the waterway and bank erosion rate are considered the three key variables that influence the likelihood of a river channel migrating into the pit. Factors that in turn influence the bank erosion rate are the erodibility of bank materials and whether or not banks and floodplain are vegetated.

Proximity of the pit to the waterway and depth of pit relative to the river channel are key variables that influence whether pit capture will occur as a result of sub-surface piping and/or spill of floodwater into the pit (Bureau of Reclamation, 2005; Langer, 2003; Packer et al., 2005). The likelihood of pit capture is greater with increased depth of pit, particularly where the base of the pit is below the lowest bed elevation of the deepest pools in the river. Pit capture is considered more likely when water flowing through pit offers the river a shorter course than currently active channel (Kondolf, 1997).

The table attempts to highlight key variables that influence pit capture, but it also needs to be recognised that there can be a range of subtle reasons and circumstances that can be locally significant in causing a river to avulse into a pit. Pumping of water from pits can lead to piping failure if groundwater inflows are high enough. Locally high velocities where there are erodible materials can cause problems. The timing of overbank flows can also be significant. If flows breakout downstream of a pit before upstream this is potentially less of an issue. Conversely if flows break out upstream and the pit is on a floodplain flow path, problems are more likely. Floodplain vegetation could also cause problems if there is a high flow resistance along vegetated flow paths that don't enter through the pit, the higher resistance of the vegetation effectively results in the direction of flows through the pit.

Table 3.1 : Risk scenarios and key variables that influence likelihood of each scenario occurring.

Risk Scenario	Key variables influencing likelihood
Lateral migration of river into the pit	Hydrology, proximity of pit to waterway, bank erosion rate (erodibility of bank/width of vegetated buffer)
Piping failure of pit walls	Hydrology, proximity of pit to waterway, depth of pit relative to channel, local groundwater conditions
Flow of water into and through the pit	Hydrology, proximity of pit to waterway, depth of pit relative to channel, local velocity, floodplain flow resistance, erodibility of pit walls.

3.3.2 Consequence

The severity of the consequences of pit capture and change in alignment of the channel will depend on the relative scale of the mining operations and the river (Norman et al., 1998), and the infrastructure that is located in the impact area. The larger and deeper the captured pit, the greater is the change in the river (Mossa & Marks, 2011; Norman et al., 1998). Significant amounts of material will be moved from the river bed and banks to fill a deep pit (Norman et al., 1998).

The effects of pit capture, are similar to instream-mining and may include lowering the bed upstream and downstream of the pit, causing river bed erosion and or channel incision and bank erosion and collapse, with damages to infrastructure. Once an avulsion through breaching of pit has occurred, the knickpoint, where the river enters the pit moves upstream, and the river bed starts to be scoured. This scouring lowers the bed of the river and progressively works its way upstream as it attempts to establish a new equilibrium and grade. Bank erosion may also occur.

Eroded sediments will be deposited in the pit, and while this is occurring there will be little transport of material past the pit to downstream areas. This leads to a discontinuity in sediment transport, and the downstream channel consequently will erode if not replenished from upstream (Norman et al., 1998). The time it takes for a river to readjust depends on the size and depth of the pit, the river's ability to transport sediment and the availability of sediment. If the supply of sediment has been limited as a result of dam construction, or the channel has eroded down to bedrock in its upper reaches, equilibrium may not be re-established for a very long time (Norman et al., 1998). This is very relevant to the Goulburn River, where it is known that there is little sediment movement downstream of Eildon (Erskine, 1996).

4. Management strategies to address risks

4.1 Introduction

There are two main approaches to reducing river related risks associated with floodplain mining:

1) Locate the pits away from the river and active floodplain so that there is lower risk of pit capture

2) Where mines are on the active floodplain implement controls to reduce risks to acceptable levels.

4.2 Safe location of pits

When it comes to considering the location and siting of mining operations, locating sand and gravel mines in upland areas away from the river valley floors is preferred. Mining upland deposits eliminates the potential for pit capture. The second choice is to locate mining on terraces and inactive floodplain areas, that are above the 100-year floodplain (Langer, 2003; Mossa & Marks, 2011; Norman et al., 1998; Packer et al., 2005; Woodward-Clyde, 1980a).

4.3 Existing guidelines to mitigate risk for pits on the active floodplain

Four publications have been identified that provide specific instruction and advice on the design and location of floodplain mining pits. These documents have been developed to provide guidance:

- on how gravel and sand extraction can be carried out in a sustainable manner (Department of Irrigation and Drainage, 2009);
- to ensure that the function of the floodplain, flood control features and infrastructure is not compromised (JE Fuller/Hydrology and Geomorphology Inc., 2004);
- on whether proposed operations are conducted in a manner consistent with law whilst also avoiding, minimising and mitigating adverse impacts to fish and their habitat (Packer et al., 2005), and;
- on the process of identifying, planning, preparing, operating and closing material sites (Woodward-Clyde, 1980a).

4.3.1 Malaysian guidelines

The first publication of note has been developed by the Ministry of Natural Resources and Environment Department of Irrigation and Drainage, Malaysia (Department of Irrigation and Drainage, 2009). This report outlines a series of policy and guidelines that should be taken into consideration when approving sand and gravel mining permits and details specific criteria to ensure sand and gravel extraction is carried out in a sustainable way for both in-stream and off-stream (floodplain or terrace) mining.

This publication sets a minimum distance between sand and gravel extraction operations and critical infrastructure. The guideline states that "*Sand and gravel should not be extracted within 1,000 metres from any crucial hydraulic structure such as pumping stations, water intakes, bridges, buildings and such structures"* (Department of Irrigation and Drainage, 2009). This minimum distance recommendation applies to extraction that is in accordance with the guidelines, as documented further below.

Figure 4.1 and Table 4.1 provide an overview of the recommended criteria that need to be considered when determining the location of the extraction area and geometry of the pit as outlined in this publication. A key criterion to highlight is the recommendation that the maximum depth of the excavation should remain above the channel thalweg. This is to minimise the impacts of a potential river capture by limiting the potential for headcutting and the potential for the pit to trap sediment (Department of Irrigation and Drainage, 2009).

It is also recommended that the depth of extraction is limited by a 10:1 line drawn from the toe of the main channel bank. The diagram appears to be a bit deceptive and there could be some confusion as to where to toe of the channel bank is. It is however obvious, that applying this criteria would lead to shallower pits closer to the main channel and deeper pits with increasing distance away from the main channel bank (with the maximum depth not to exceed the channel thalweg).

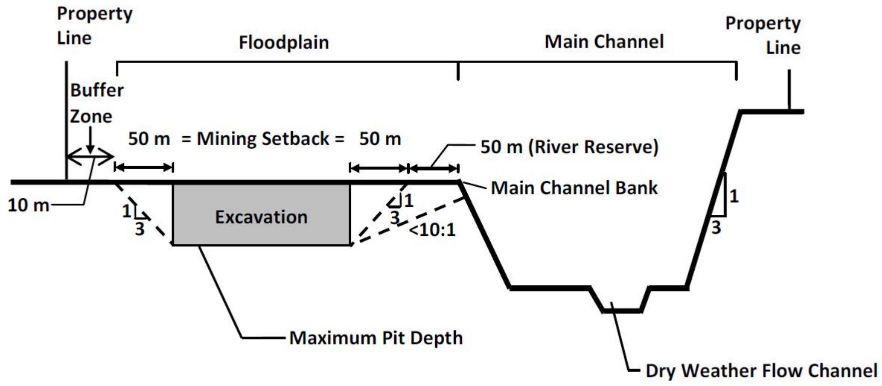

Figure 4.1 : Extract from Department of Irrigation and Drainage Malaysia River Sand Mining Management Guideline Document (Department of Irrigation and Drainage, 2009). Floodplain pit geometry illustrating recommended criteria. Refer also to Table 4.1 for clarification of recommendations.

Table 4.1 : Recommendations for floodplain or terrace mining outlined in Department of Irrigation and Drainage Malaysia River Sand Mining Management Guideline Document (Department of Irrigation and Drainage, 2009). Refer also to Figure 4.1.

Item	Description
Mining Setback	Floodplain extraction should be set back from the main channel to provide a buffer and should be designed to withstand the 100-year flood. The excavation must be a minimum of 50 m from the main channel bank. Adequate buffer widths and reduced pit slopes gradients are preferred over engineered structures which require maintenance into perpetuity. To avoid possibility of stranding fish, extraction should be conducted above the 25-year ARI level.
Maximum depth	Maximum depth of floodplain extraction - should remain above the channel thalweg Maximum depth of floodplain extraction as determined by a 10:1 line drain from the elevation of the toe of the main channel bank (i.e. a pit with 50 m buffer may be considered to have a maximum depth of 5 m)
Batters	Side slopes of floodplain extraction should range from 3:1 to 10:1
Stockpiles	Place stockpiled topsoil above the 25-year return period or ARI level

4.3.2 Arizona guidelines

The second publication that provides details of specific limits or criteria for the design and location of floodplain pits has been developed by the Flood Control District of Maricopa County (near Phoenix, Arizona) (JE Fuller/Hydrology and Geomorphology Inc., 2004). The policies and criteria define development standards that are required for sand and gravel extraction within Flood and Erosion Hazard Zone planning layers.

The flood control district of Maricopa Country has established a series of sand and gravel mining policies to protect public health, safety, and welfare and to protect the natural and beneficial functions of floodplains, and to minimise the expenditure of public funds for repair of infrastructure in the riverine environment (JE Fuller/Hydrology and Geomorphology Inc., 2004). These policies are repeated here as follows:

1) Aggregate mines should be located outside of the regulatory floodway whenever feasible.
2) Aggregate mines should be located outside of the erosion hazard zone whenever feasible.
3) If aggregate mines are located within the regulatory floodway or erosion hazard zone and no structural flood control measures are provided, the maximum excavation depth should be no greater than the natural channel invert elevation shown on the effective floodplain delineation study.
4) If aggregate mines within the floodplain or erosion hazard zone are excavated below the natural channel invert elevation shown on the effective floodplain delineation study, then engineered grade control structures should be provided at any point where the 100-year flood could enter the excavation, or

engineered flood control structures shall be provided to prevent the 100-year flood from entering the excavation.

5) Aggregate mines shall have no adverse floodplain, erosion, or sedimentation impacts on any adjacent or off-site property.

6) Aggregate mining operations must have a reclamation plan that assures the long-term stability of the excavation and the adjacent river system.

7) Aggregate mining operations shall be compatible with the recommendations and policies specified in the approved watercourse master plan for that watercourse.

8) Technical reports submitted in support of aggregate mining floodplain use permits should be prepared by experienced Arizona-registered professional engineers with relevant expertise in hydrology, hydraulics, sediment transport, river mechanics, fluvial geomorphology, and local stream systems.

Figure 4.2 and Table 4.2 provide an overview of the recommended criteria that need to be considered when determining the location of the extraction area and geometry of the pit. The maximum depth of the pit is determined by a 10:1 line drawn from the toe of the main channel bank. There is no specific criteria limiting the depth of excavation to the natural channel invert, however the guidelines do specify that if extraction is to go deeper than this level, engineered grade control structures or flood control structures need to be provided.

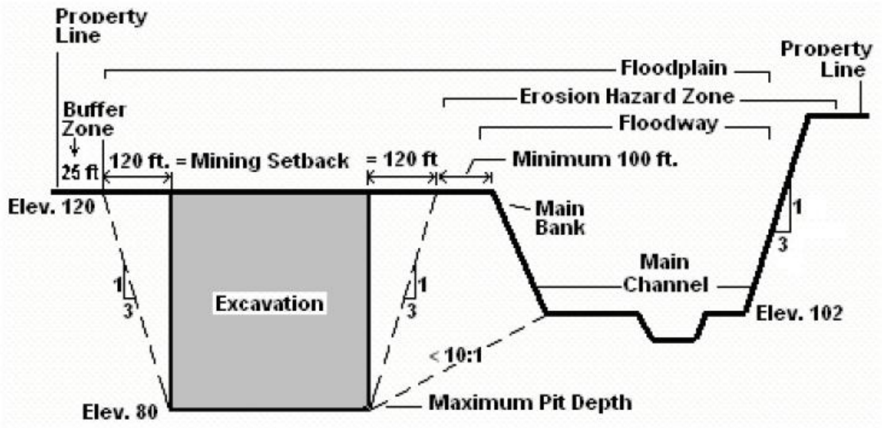

Figure 4.2 : Extract from Sand and Gravel Mining Floodplain Use Permit Application Guidelines for the Flood Control District of Maricopa Country (JE Fuller/Hydrology and Geomorphology Inc., 2004). Floodplain pit geometry illustrating recommended criteria. Refer also to Table 4.2 for clarification of recommendations.

Table 4.2 : Recommendations for floodplain excavations as outlined in the Sand and Gravel Mining Floodplain Use Permit Application Guidelines for the Flood Control District of Maricopa Country (JE Fuller/Hydrology and Geomorphology Inc., 2004). Refer also to Figure 4.2.

Item	Description
Mining Setback	The excavation must be set back a minimum of: · 25 feet or 7.6 metres from the erosion hazard area, and · 100 feet or 30.5 metres from the main channel bank, and · 500 feet or 152.5 metres from any bridge or utility crossing, and · Three times the difference between the natural ground elevation at the mining buffer line and the minimum elevation of the excavation (25 feet or 7.6 metres from the property line) and the minimum level of the excavation.
Depth of excavation	The maximum depth of excavation is determined by a 10:1 line drawn from the elevation of the toe of the main channel bank. If excavation occurs below the level of the natural channel invert than engineered grade control structures will be required at any point where the 100-year flow could enter the pit or engineered flood control structures should be provided to prevent the 100-year flood from entering the excavation.

The guidelines are also very clear in stating that more detailed engineering analysis is required to support any application that does not meet in the intent of the policies documented (JE Fuller/Hydrology and Geomorphology Inc., 2004). A high level of specialist and design skills is required to support these applications.

4.3.3 NOAA guidelines

The United States National Marine Fisheries Service has developed gravel extraction guidelines aimed to protect fish habitat (Packer et al., 2005). Relevant recommendations include:

- Gravel mining should occur in upland areas, away from rivers and floodplains if possible.
- Pit excavations should be sited outside the channel migration zone and as far from the stream as possible.
- All gravel extraction operations be managed to avoid or minimize stream or riparian disturbance:
  - Gravel pits not be extracted below the water table
  - Berms and buffer strips be established to protect a pit from stream capture and that these be maintained for several decades
  - All support and processing operations be done outside the riparian zone
  - Gravel stockpiles, overburden and and/or vegetative debris not be stored within the riparian zone and be disposed of properly

  - Access roads not encroach into riparian areas
  - Riparian zone protection extend well upstream and downstream from extraction operations
- An integrated environmental assessment, management and monitoring program be part of any gravel extraction operation.
- Mitigation be an integral part of gravel extraction projects:
  - avoidance of direct or indirect impacts or losses
  - minimization of the extent or magnitude of the action
  - repair, rehabilitation or restoration of integrity and function
  - reduction or elimination of impacts by preservation and maintenance; and
  - compensation by replacement or substitution of the resource or environment.
- Cumulative effects of multiple extractions be considered

4.3.4 Alaska guidelines

The United States Fish and Wildlife Service developed guidelines for gravel removal following a study of 25 floodplain mining sites in Alaska (Woodward-Clyde, 1980a, 1980b). Relevant recommendations include:

- Pits should be located in areas where they will have a low probability of diverting channels into the mined area. This means they should be located on terraces, inactive floodplains, or stable islands with the recommended buffer. Terraces are preferred because of the reduced probability of channel diversion.
- The natural or man-made buffer design should take into consideration:
  - its location with respect to the active channel(s) and the extraction area;
  - the width required to withstand erosion with jeopardising the integrity of the buffer
  - the height of the buffer required to divert floods
  - the size of the stream (minimum width ranging from 150-250 m for medium to large streams)

4.4 Other controls to reduce risk of pit capture

A number of methods are stated in the literature as options that may assist in the prevention of floodplain mining impact on river and infrastructure. These are summarised here.

4.4.1 Construction of a levee to keep flood waters out of pit

Langer (2003) states that the impacts from an avulsion and pit capture can be avoided by construction of a levee along the edge of the stream. The levee is designed with armoured spillways that control where the levee will be “breached” by the stream during flooding. The spillway allows water to leave the channel and temporarily flow over the floodplain but keeps the stream from creating a new channel and keeps the bedload in the stream. There are a number of issues associated with levee construction on floodplains. They change the flooding behaviour of the floodplain, and by limiting flooding in one area this may result in greater flooding in another area. During extreme floods, water levels may overtop levees and even when levees have been constructed to highest standards they can still breach and fail (CIRIA, 2013).

4.4.2 Design of structures to allow safe flow through pits

The design of structures that allow flow to enter into pits is cited as another option in the literature (Bureau of Reclamation, 2005; JE Fuller/Hydrology and Geomorphology Inc., 2004; Schnitzer et al., 1999). This entails construction of engineered grade control structures to convey water into and out of the pit. These require detailed engineering design to ensure that structures remain stable for the range of flows experienced. A high rate of energy dissipation is to be expected at the point where flow enters the pit, with a high potential for scour at the toe of the grade control structure. The batters of the grade control structure also need to be sufficiently protected, taking care to tie these into stable non-erosive surface to prevent flanking. Schnitzer et al. (1999)

acknowledge that retrofitting sites where extraction is deeper than the channel is difficult, due to the significant height and gradient over which the structures must convey flow.

The Bureau of Reclamation (2005) in a review of the rehabilitation of floodplain mining pits suggest that for large and deep pits, in addition to maintaining the integrity of dykes and levees that separate the pit from the river, providing a hydraulic connection to the pit at the downstream end may assist in reducing avulsion risk. By connecting the river at the downstream end, avulsion risk is lowered due to decreased velocities at the opening. To support this claim, the Bureau of Reclamation (2005) cite the earlier study by Schnitzer et al. (1999) which showed that following major flooding in Oregon, gravel pits where floodwaters backed into the gravel pit before the river over-topped the levees generally received the least amount of damage. This is suggested to be due to the reduced hydrostatic pressures applied to the back-side of the levee being equal to that on the river side of the levee (Bureau of Reclamation, 2005).

Providing a hydraulic connection at the downstream end of the pit may assist in preventing one potential failure mechanism, the spill of floodwater into the pit. It does not address failure by lateral migration or piping which would still be a threat when the pit has low water levels.

4.4.3 Vegetation buffers and bank revetments

Vegetation buffers may reduce the potential of stream capture for existing floodplain pits (Mossa & Marks, 2011). The intent here is that the vegetation increases the resistance of floodplain areas between the pit and river to erosion, and therefore limits the potential for lateral migration or channel avulsion to occur. Bank revetments either on the river side, or as treatments on the battered slopes of pit, can also increase the resistance of these surfaces to erosion (Klingman, 1998). Norman et al. (1998) states that while vegetative buffers may reduce the probability of a river avulsion in the near term, they may only serve to delay the inevitable capture of the pit.

4.4.4 Avoid siting pits in a 'channel migration zone'

In Washington State and Arizona , floodplain mine regulators have adopted the concept of a Channel Migration Zone to assist in the identification of suitable sites (Rapp & Abbe, 2003). This considers the dynamism of the river channel through historical analysis of channel migration to identify areas that are disconnected from river migration. Mining is restricted to floodplain terraces or areas of the floodplain where there are structural measures in place to limit the migration of the channel.

5. Floodplain mining in the Goulburn Valley

This review has examined the impacts and risk associated with floodplain mining as documented in the Australian and International literature.

Most of the floodplain of the Goulburn River in the Shire of Murrindindi (between Kerrisdale and Molesworth) has been identified as an *Extractive Industry Interest Area*, a source of gravel for Melbourne. If mining were to proceed to the extent identified by DEPI review documents (Olshina & Burn, 2003), there would be significant implications for the Goulburn Broken CMA.

Local, national and international case studies show that pit capture and subsequent river channel changes, are a common consequence of floodplain mining. There has already been one example on the Goulburn Floodplain where Island Creek diverted into a gravel mine as a result of piping failure; a road crossing and riparian vegetation were destroyed.

Avulsions are a natural process along the Goulburn River (Erskine et al., 1993). This process is commonly initiated by floodwaters spilling into floodplain depressions. The floodplain pits that are created by sand and gravel extraction in the Goulburn Valley are floodplain depressions, but they are substantially deeper and wider than natural depressions and therefore represent a greater threat to the stability of the river. It is also noted that due to Lake Eildon, there is very little sediment movement through this reach. If a pit capture were to occur, the time it takes to recover and the extent of the impacts could be far greater as the system has a limited sediment supply as a result of flow regulation.

There are nine existing mines in the Goulburn Valley, three of these have surrendered their operations and six remain current (Figure 5.1). When the existing gravel mines, and mining proposals, on the Goulburn River floodplain are compared with international case studies there is cause for concern:

- The current mines are deeper than most of the mines discussed in the case studies. This increases the risk of pit capture.
- The extent of the Extractive Industry Interest Area identified by DEPI (Olshina & Burn, 2003) would suggest a potential for mining intensity that exceeds that described in most case studies.
- Some of the mines are positioned close together, and this could increase the risk of pit capture e.g. WA232 and WA781. The same two pits are also close to the Hume Freeway (Figure 5.1).
- WA1889 is only 130 m distance from the Bridge for the Melbourne to Sydney Railway, the proximity of the mine and its depth increases the risk of pit capture with potential to impact on this structure.

The *Extractive Industry Interest Area* occurs in a reach of the Goulburn River which is identified as having the highest environmental values for significant fauna and ecological vegetation classes (GBCMA, 2005). It also has the highest social values in the categories of fishing and landscapes. This reach is recognised as a heritage river under the *Heritage Rivers Act*, Victoria, 1992 because of its high environmental and social values and is covered by an environmental significance overlay in the Murrindindi Planning Scheme. Many of these values may be at risk from the consequences of gravel mining, and in addition, there is potential for gravel mining to damage key infrastructure.

Work Authority	Status	No. of pits	Pit Areal Extent (ha)		Pit Depth (m)	
			Existing	Final Approved	Existing	Final Approved
WA374	Surrendered	2	0.6	?	?	?
WA151	Surrendered	1	0.9	?	?	?
WA141	Surrendered	1	2.8	?	?	?
WA516	Current	1	3.8	3.8	5-10	30
WA45	Current	5	20	20	23	23
WA1443	Current	1	4.8	4.8	5	5
WA1189	Current	1	13.1	33	18	28
WA781	Current	2	13.5	56	14.5	15?
WA232	Current	2	5.5	5.5	?	15?

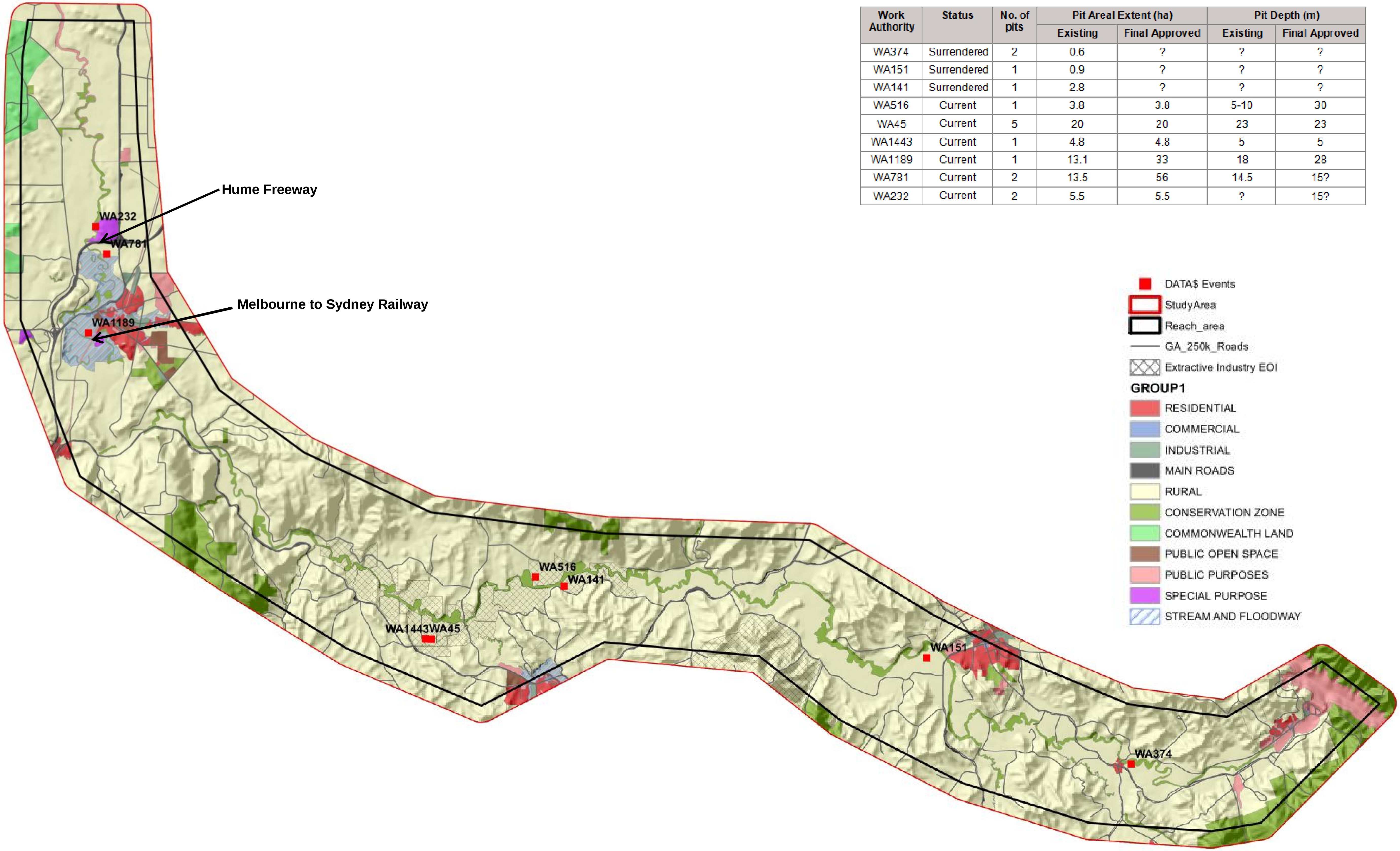

Figure 5.1 : Goulburn Valley showing location of floodplain mining extraction sites and their position in relation to different planning zones. The position of key infrastructure such as Hume Freeway and Melbourne to Sydney Railway are shown. The table outlines some basic information known for these pit areas.

6. Summary

Sand and gravel extraction from floodplain areas is generally perceived to have less impact than extraction from stream channels. However, major floodplain impacts can occur if, during flooding the stream creates a new channel through the pit.

If pit capture occurs, physical impacts include bed degradation and aggradation, bank erosion and channel widening, with these physical impacts often extending many kilometres away from the pit. Infrastructure such as road crossings and services that lie within the area of physical impact may also be damaged or destroyed.

Three main risk scenarios have been identified that have the potential to result in a pit capture. These are:

- Lateral migration of river channel into the pit
- Sub-surface piping into pits and subsequent failure of pit walls
- Flow of water into and through the pit

The likelihood of a pit capture occurring via one of these three risk scenarios is a function of a number of variables. Hydrology is a key variable that influences likelihood, as it is the flow of water into a pit from the river that leads to its capture. Local hydraulic effects are also important such as the flow velocity adjacent to erodible floodplain and bank material. Other variables that are important are the proximity of the pit to a waterway and the depth of the pit relative to the channel. Pits in close proximity to a waterway and where extraction has continued to a depth lower than the thalweg of the adjacent waterway will pose a greater risk, than pits that are positioned further away from the waterway where extraction does not extend below the level of the thalweg.

The consequences of a pit capture depends on the relative scale of the mining operations and the river and the infrastructure that is located in the impact area. The larger and deeper the captured pit, the greater the potential change is to the river. The physical process of pit capture have been well documented from case studies, incision upstream and downstream of the pit are expected, with bed adjustments continuing until the river establishes a new equilibrium and grade. Any infrastructure which traverses the impacted area is at risk of being damaged during this period of adjustment.

A number of methods exist to prevent floodplain mining impacting on the river. None of these options can be relied upon, in that even if designed to the highest standard they can still fail. They may also generate problems elsewhere. Levees can be constructed to keep flood waters out of the pit, however by limiting flooding in one area this may result in greater flooding in another area. Structures can be designed to manage flows into and out of the pit, but it is difficult to make these work and remain stable in the long term, particularly for sites where pits are deeper than the channel. Vegetation buffers and bank revetments serve to increase the resistance of the surfaces to erosion.

Not mining on the active floodplain and restricting operations to terraces and upland areas is an effective way of mitigating the risk of pit capture. Choosing to mine only in inactive floodplain areas, or areas determined as disconnected from the river through historical channel migration analysis also reduces the risks.

Technical guidelines have been developed in a number of jurisdictions to provide specific instruction and advice on the design and location of floodplain pits to ensure that sand and gravel extraction is carried out in a sustainable manner and that the function of the floodplain, flood control features and infrastructure is not compromised.

These documents set specific criteria regarding the location and depth of floodplain mining operations and their proximity to infrastructure and waterways. The guidelines and criteria that have been set regarding the depth of extraction is based on recognition that avulsion risk is increased where the depth of the pit extends below the level of the adjacent waterway and that pits that lie closer to the waterway are more susceptible to capture than those positioned further away.

However, the guidelines do vary in what they recommend and the justification behind different criteria is not always clear. For example, one publication states 1000 m as being an appropriate setback from critical infrastructure whereas another recommended 150 m. One publication is stronger in its recommendation that extraction should not go below the thalweg whereas another indicates this can proceed as long as there is sufficient controls in place to either prevent flow from entering the pit or manage the flows that do enter the pit.

Pit capture and associated changes in channel alignment are a genuine concern in the Goulburn Valley. The scale of the operations and their positioning relative to the river and key infrastructure indicate that significant physical and infrastructure impacts will continue to occur.

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Important note about this report

The sole purpose of this report and the associated services performed by Jacobs is to undertake a review of the impacts of floodplain mining on river systems in accordance with the scope of services set out in the contract between Jacobs and the Goulburn Broken CMA. That scope of services, as described in this report, was developed with the Goulburn Broken CMA.

Jacobs derived the data in this report from information sourced from the Goulburn Broken CMA and/or available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

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