Pilbara creek diversions

Resilience gained through increased ore recovery and an integrated approach to design

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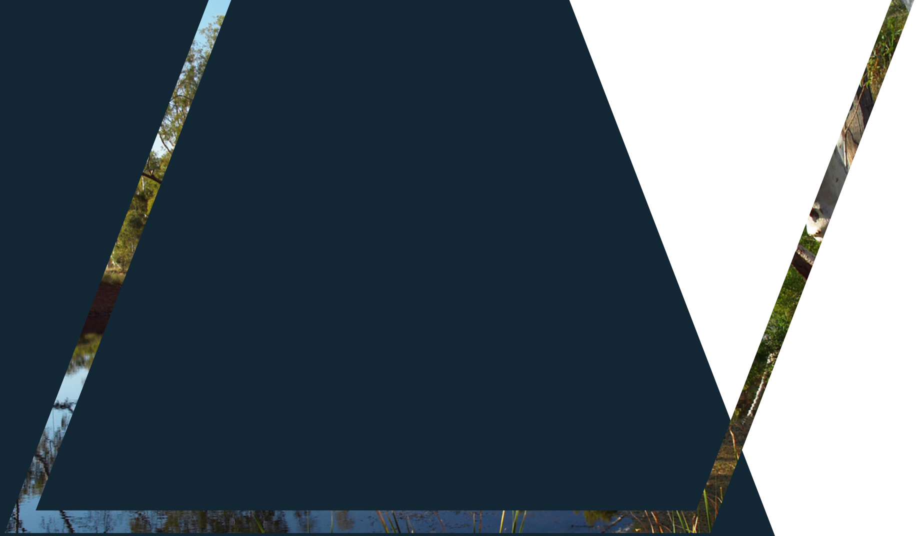


Abstract

Over recent years there has been a significant increase in the number of miners in the Pilbara region of Western Australia, targeting channel iron deposits (CID) located in valleys, intersected by ephemeral creeks and below the groundwater table. The falling iron ore price has triggered a drive to reduce cost and maximise yield. Creek diversions provide an opportunity to maximise the utilisation of orebodies and extend the life-of-mine.

Creek diversions that are required during mining operations to access ore and provide flood protection have been historically constructed as uniform engineered channels, designed primarily for flow conveyance while minimising earthworks costs; however, the design of diversions becomes more complex when they are required to function in a similar way to the existing creek system during operations, and remain stable during more extreme events that would typically occur following mine closure, in accordance with current regulatory guidance.

The design specifications for closure are often more rigorous than the operational phase, and could incur significant additional cost to implement retrospectively if not planned and designed upfront.

The complexity of diversion design depends on site-specific factors such as: the size of the creek to be diverted; hydrology; corridor restrictions; geomorphology; hydrogeology; geology; environmental and heritage values; potential impacts and the risk to operations and environment.

The complex interactions of these factors must be well understood and hydraulic modelling undertaken to characterise the existing creek system, demonstrate the diversions, provide adequate flood protection during operations, and can function in a similar way to the existing system following mine closure.

This paper presents key design considerations for Pilbara creek diversions, operational and closure requirements, mine planning considerations, risks, cost saving opportunities, and the benefits of an integrated approach to design.

Introduction

The Pilbara region of Western Australia is one of the world's most productive iron ore mining areas and is characterised by ancient arid landscapes and highly-variable hydrology.

Historical mining has targeted above water table ore deposits elevated above creek lines where possible to reduce cost. However, as these deposits become depleted there is now an increased focus on mining channel iron deposits (CID) which is often associated with valley floors and ephemeral creek lines.

This is demonstrated by a regional assessment of CID extents and iron ore (Fe) Mines and Deposits shown in Figure 1. A large proportion of these mines are targeting or plan to target high-grade CID ore associated with existing creek systems. Figure 2 shows outcropping and inferred subcropping CID extents, which suggests there are vast quantities of CID ore deposits throughout the Pilbara region, intersected by major creeks that could be mined at some point in the future using diversions.

The mining of this CID ore requires surface water management measures to prevent the ingress of floodwater into pits during mining operations. CID ore located beneath existing creek lines can be left in situ and retained without directly impacting on the creek or the creek can be diverted to allow the ore to be mined. Diversions and flood protection bunds/levees that are required during mining operations to allow mining of CID beneath creek systems are typically designed to provide protection up to the one per cent annual exceedance probability (AEP) flow event. Operational diversions have historically been constructed as uniform engineered channels designed primarily for flow conveyance while minimising earthworks costs. However, the design of creek diversions becomes more complex when they are to remain at mine closure and are required to function in a way that is consistent with the existing creek system (that is, the hydraulic, ecological and geomorphological values of the diversion match the conditions in the reference reach (Department of Resources, Energy and Tourism, 2008)).

An understanding of the hydrology, hydraulics, geomorphology and ecological processes of the existing creek system is therefore critical to the design of diversions for closure. This information can be used to inform the design of diversions while subsequent hydraulic and sediment transport modelling can be used to verify that the proposed designs function in a similar way to the existing system.

This paper has been developed based on our experience gained while working on a number of Pilbara creek diversions over the past ten years. The paper presents general decision making and design considerations specific to the construction of major creek diversions in the Pilbara, with consideration of operational and closure requirements.

The design of creek diversions becomes more complex when they are to remain at mine closure and are required to function in a way that is consistent with the existing creek system.

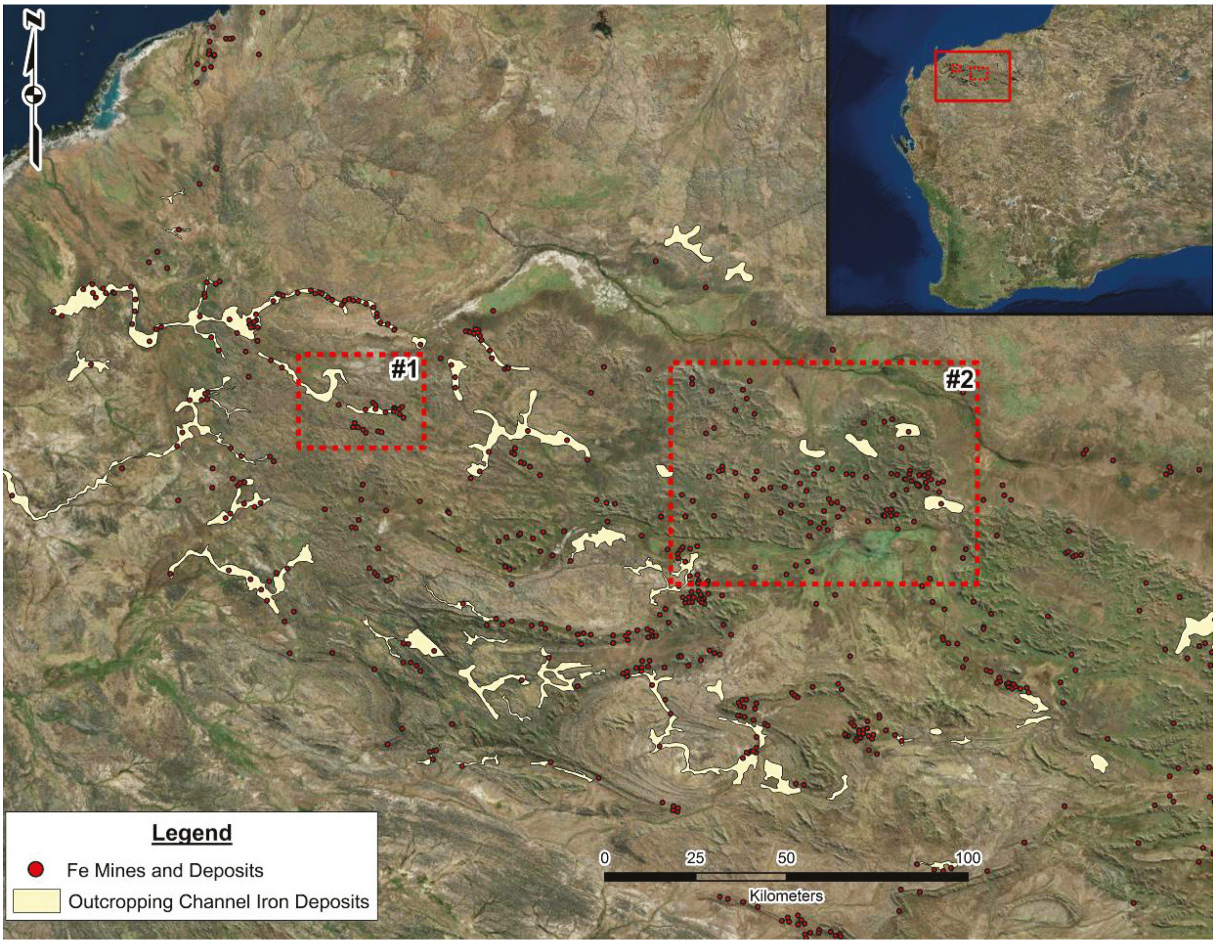


FIGURE 1 – Outcropping channel iron deposit extents and Fe mines and deposits mapped using regional geology maps and MINEDEX database (Department of Mines and Petroleum, 2017). Inserts #1 and #2 are shown in Figure 2.

Diversion decision-making

Why divert a creek? The simple answer to this question is: diversions help maximise the tonnes of CID ore recovered and the associated profits. However, this is only achieved when the cost of planning and constructing the diversion are out weighed by the value of the CID ore recovered and it can be demonstrated that the proposed diversions do not adversely impact on the environment.

There are many ways to divert a creek, which also needs to be considered in the decision process, including:

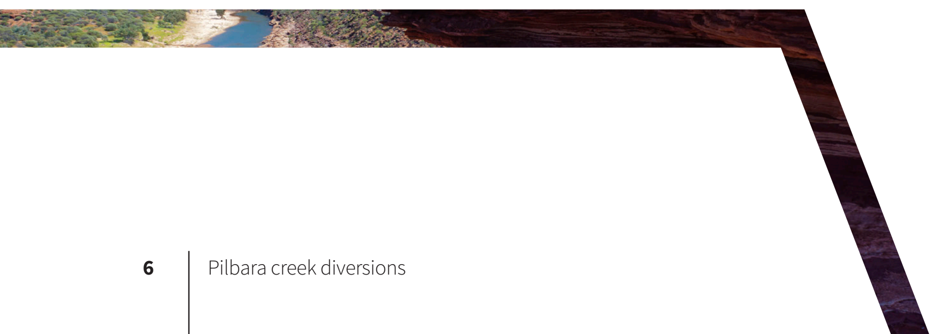
- Diverting around a pit
- Diverting through a pit backfilled back to the natural surface
- Where there is insufficient backfill, constructing a landbridge to convey the flow-through of a partially backfilled pit.

The scale of the diversion is important in the Pilbara; small catchments less than ~1 km^2 area are often allowed to flow into the pits, while other minor creeks are diverted as a business as usual mining activity. The approvals associated with diverting minor creeks and drainage lines are generally less involved as they have smaller catchment areas, have smaller flows and generally have less significant environmental values. However the diversion of major creek systems is considerably more complex. In Western Australia, consultation with the Department of Mines and Petroleum (DMP), Environmental Protection Authority (EPA) and Department of Water (DoW) is needed to identify the level of assessment and studies required.

Mining of ore situated underneath major creek systems is often left until later in the mine plan to reduce upfront capital expenditure (capex). This is not always possible particularly where the ore is heavily constrained by topography, in which case diversions may be required early in the mine plan to access the ore. In other cases, creek ore intersections are left in place and left unmined, due to approval lead times associated with major creek diversions and the complexities associated with the design and mine planning.

Why divert a creek? The simple answer to this question is: diversions help maximise the tonnes of CID ore recovered and the associated profits.

Analysis of typical CID-creek intersections in Figure 1 and Figure 2 suggests that the value of ore potentially recovered through the use of diversions could be in the order of hundreds of millions, possibly billions of dollars per CID-intersection depending on market conditions. Therefore, it would be prudent to fully explore the business case for diverting creeks to mine creek ore. While there are several technical, operational and environmental risks to be managed, with appropriate engineering design and risk management processes in place, the significant financial benefits of diversions can be realised.



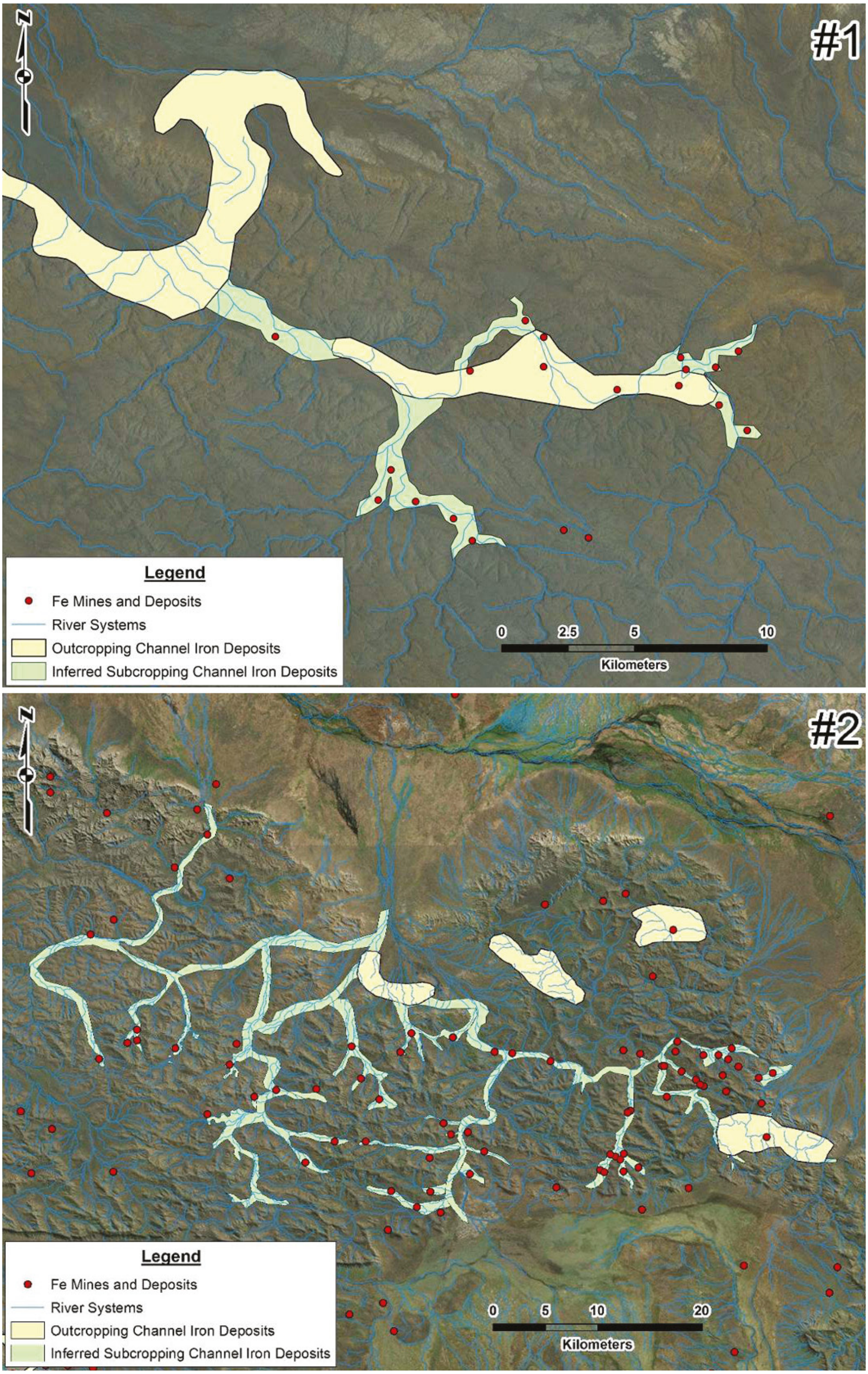


FIGURE 2 –Outcropping and inferred subcropping channel iron deposit extents mapped using regional geology maps (Department of Mines and Petroleum, 2017), aerial imagery analysis and interpretation of publicly available reports and presentations. The numerous intersections with Pilbara creek systems are also shown (refer to inserts #1 and #2 in Figure 1).

Options analysis

The most effective way to navigate the complexities associated with diversion decision-making is to utilise a structured methodology that allows the costs of all potential diversion options to be assessed and compared, including the option of ‘doing nothing’ (i.e. don’t divert and leave creek ore in the ground). The risks and environmental/social impacts associated with each of the options should then be reviewed to allow a holistic assessment of all options.

Firstly, one has to decide whether to divert the creek or not. To make this assessment, the value of the stranded ore needs to be determined. Once the economic value of the stranded ore has been assessed and confirmed to be positive, the key decisions associated with diversion should be mapped (i.e. the extent of diversion, method of diverting and timing of the diversion). A strategy table is a useful approach to map these decisions and ways in which they can be achieved. A table showing some hypothetical options is presented in Figure 3.

Once all possibilities have been mapped, diversion options should be developed aligning to various strategic themes; (e.g. minimising cost, maximising recovered ore etc).

Each of the diversion options, including the do nothing option, should be calculated and compared by subtracting the cost of constructing the diversion from the value of the ore recovered. A typical comparison of the identified options is presented in Figure 4.

The decision on whether to divert may change when we consider the costs needed to develop a new mine area to sustain ore production. That is, diversions also have the potential to extend the mine life and delay the capex associated with developing a new mine.

Once the decision has been made to divert, the relative costs associated with each of the alternative options can be normalised and compared directly using cost per tonne of ore recovered ($/t.)

The analysis described above is from a cost perspective only, considering the operational requirements only. In order to fully evaluate the potential options, the costs associated with potential environmental/social risks need to be quantified and considered in the decision-making process; however, with sound engineering design and risk management processes in place the likelihood of these risks occurring can be minimised.

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Mapping the decision associated with the problem

Do you divert the creek?	What do we divert?	How do we divert?	When do we divert?
■ No	■ Nothing	■ We don't	■ Never
⬟ ◆ ▲ ● Yes	⬟ ◆ The entire creek	◆ ▲ ● Around	▲ Before we start operating
-	◆ ● Some of the creek	Through - backfill	● At the end of current operations
-	-	⬟ Through - land bridge	⬟ ◆ Midway through current operations

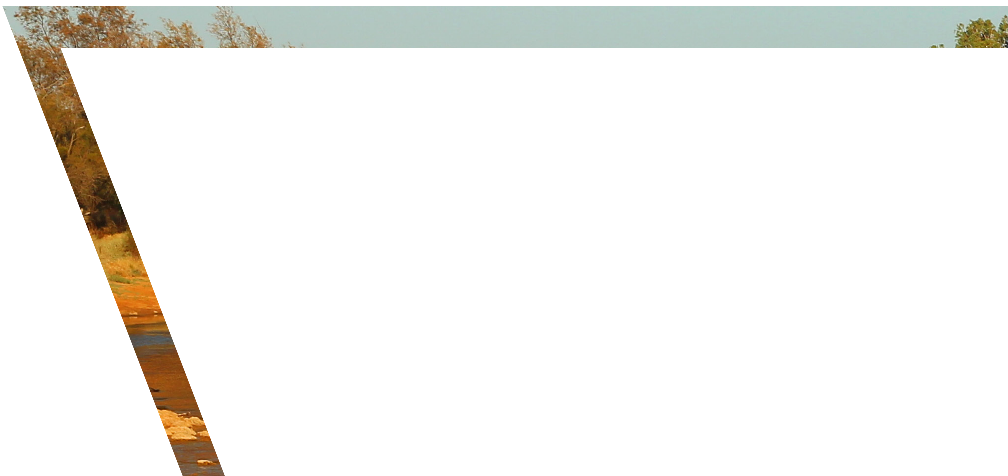
FIGURE 3 –A hypothetical strategy table mapping the decisions associated with major creek diversions.

The options		
1	Do nothing	■
2	Divert at minimal cost	●
3	Divert to maximise recovered ore	▲
4	Diver with minimal disruption to operations	◆
5	Divert under topographically constrained conditions	⬟

Mine planning considerations

While leading practice environmental management for watercourses is generally applied across the industry, operational and financial constraints are always considerations. From an operations perspective, the requirement for a creek diversion to convey water between two points in a safe, controlled and predictable manner must be considered in addition to environmental and social considerations. There are a range of operational considerations that include (Markham, 2012; Markham, Atkinson and Pearson, in press):

- **Flood protection** – operational diversions should provide adequate protection from flooding to minimise the risk of disruptions to operations and provide a safe working environment. Flood protection bunds/levees are required to redirect floodwater into and out of the diversions without entering the pits. They are generally designed to provide protection (with freeboard) during the one per cent AEP design storm event. Mine sites with shorter/longer design lives may consider alternative design AEPs using a risk-based approach.
- **Corridor restrictions** – dictated by current and planned infrastructure and mining layout.
- **Mine infrastructure** – the costs associated with relocating mine infrastructure should be considered. This also includes the potential impact the diverted creek may have on this infrastructure during flood events and any necessary upgrades to maintain the same level of serviceability.
- **Mine planning** – the timing of access to pits, haul road access routes, waste dump designs, traffic management and other considerations will heavily influence the design and construction of diversions and can have a significant effect on cost.
- **Construction planning** – dictated by infrastructure and mine plan considerations. Construction plans developed with the aim of optimising haulage where possible to reduce cost.
- **Material classification** – there is a need to ensure that the material to be excavated when constructing diversions, as well as other sources of material proposed for construction is adequately characterised by geotechnical drilling programs and laboratory testing during the early design phase. This will confirm that the sources of material required for construction of diversions and any other associated structures/landforms have suitable geotechnical properties and that there is sufficient volume available when required. Incorrect assumptions about the volume and geotechnical properties of the material can impact on cost. Therefore, this characterisation is needed to accurately cost the diversions and mitigate the risks associated with construction and approval delays. Limited availability of appropriate construction materials may compromise diversion performance.



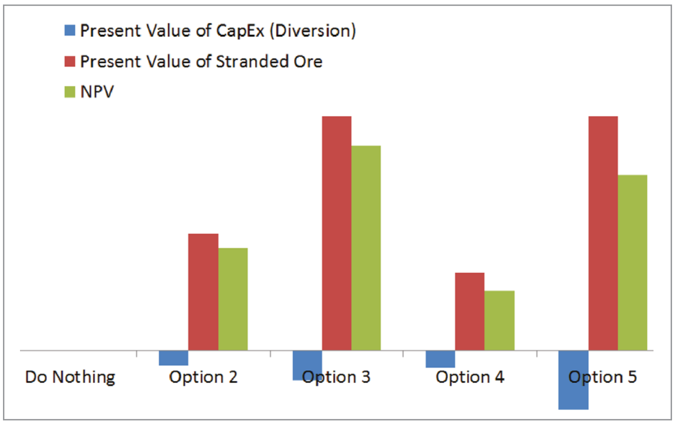
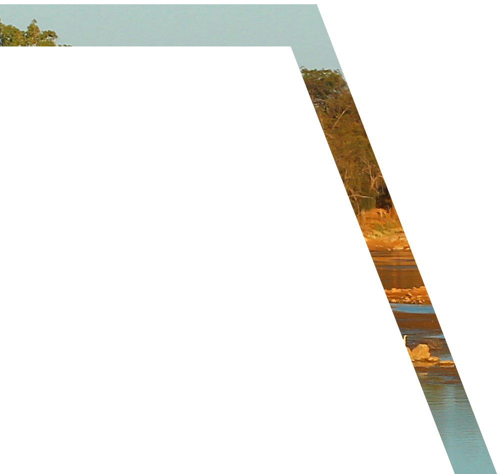


FIGURE 4 – Hypothetical diversion option analysis (capex – capital expenditure; NPV – net present value).

- **Health and safety** – a diversion functions as an operating hydraulic structure. Natural rivers do not have Health, Safety and Environment (HSE) policies, safe inspection points, guard rails and the like. Slope stability and potential failure modes should be assessed in areas of cut. Slope failures pose an HSE risk during construction and also pose a risk of blocking the diversion, which would lead to increased flood water levels (backwater effects) that could fl ow into pits.
- **Monitoring and maintenance costs** – diversions should be monitored and maintained where necessary.
- **Pit/diversion buffer** – The Department of Industry and Resources WA (1997) published the Safety Bund Wall around Abandoned Open Pit Mines Guideline. The guideline provides the methodology to calculate the buffer needed between the pit crest and abandoned bunds to cater for potential wall collapse (potentially unstable pit wedge zone) in future. Similar buffers should be provided between the pit crests and the diversions and flood bunds/levees to reduce the risk of direct connection of the creek with the pits due to pit wall collapse or channel migration.
- **Materials movement and scheduling** – a material movement schedule will confirm the sources and volumes of materials to be excavated, the haul routes and disposal locations. Optimisation of the haulage routes in consultation with mine planners and operations managers can significantly reduce cost.
- **Flood warning systems** – there are risks associated with experiencing a major flood event while constructing the diversion, as this could significantly delay works and result in loss of alluvial sediment and topsoil stockpiles. This flooding also presents a significant safety risk. Real-time flood forecasting systems are commonly in Australia to provide more proactive emergency response to flooding. Similar systems can be used during mining operations to provide advance warning of flooding and reduce the risk of delays to both construction activities and mining operations.



The costs associated with relocating mine infrastructure should be considered. This also includes the potential impact the diverted creek may have on this infrastructure during flood events and any necessary upgrades to maintain the same level of serviceability.

The regulator’s perspective

Watercourses (creeks, streams or rivers) are key components of landscapes and communities and are valued for their water supply, recreation and environmental values and for aesthetic and cultural reasons. Proposals to divert watercourses therefore may require regulatory approval. Regulators recognise the geomorphologic, hydrologic and ecological components of a watercourse, as well as its hydraulic and engineering components and that a diversion should be self-sustaining, maintain or add to river heath values, and not create an unstable landform whereby the diversion needs to be maintained (Markham, Atkinson and Pearson, in press).

At the time of writing, there is no Australia-wide guideline for designing and managing mine site stream diversions. The approach of the regulator varies between the states and territories. While the existing literature, particularly the Australian Stream Rehabilitation Manual (Rutherfurd, Jerie and Marsh, 1999), provides a guide to Australian stream rehabilitation in general, it does not contain specific detail pertaining to mine site stream diversions.

In Western Australia, mining companies are required to undertake initial consultation with the DMP, EPA and DoW to discuss the proposed diversions and identify the level of assessment and studies required. Proposed creek diversions must be included in mining proposals submitted to the DMP for approval. This document should provide the diversion design details, as well as supporting reports and data, demonstrating that the diversion will maintain the hydrological regimes, quality and quantity of surface water to the extent that existing and potential uses, including ecosystem maintenance, are protected. The mining proposal must also contain a mine closure plan developed in accordance with the Mine Closure Guidelines (DMP and EPA, 2015), outlining the diversion designs as well as rehabilitation and monitoring plans needed to ensure that diverted sections of creek function in a way that is consistent with the existing creek system. The assessment and approval processes for mining proposals often require advice or endorsement from other environmental regulators including the EPA and DoW. Consultation with the DoW will determine whether a section 11/17/21A permit to interfere with bed and banks of a watercourse is required (Section 11, 17 and 21A of the Rights in Water and Irrigation Act 1914).

Diversion designs in Western Australia are typically developed in a manner consistent with the philosophies outlined in the ACARP Guidelines (Hardie and Lucas, 2002; Alluvium, 2014), DNRW Guidelines (Department of Natural Resources and Water, 2008), DNRM Guidelines (Department of Natural Resources and Mines, 2014) and the Australian Stream Rehabilitation Manual (Rutherfurd, Jerie and Marsh, 1999) as well as the Leading Practice Sustainable Development Program (LPSDP) for the Mining Industry – Water Management Handbook (Department of Resources, Energy and Tourism, 2008). The LPSDP Water Management Handbook states that *‘leading practice design of watercourse diversions requires that hydraulic, ecological and geomorphological values of the diversion match conditions derived from a reference reach’* (Department of Resources, Energy and Tourism, 2008).

The more recent ACARP Guidelines provide design and management guidelines for stream diversions for the Bowen Basin, including tables of threshold hydraulic modelling parameters for diversion design. The design principles are often applied to other geographic regions both within Australia and overseas. Bowen Basin river diversions design and rehabilitation criteria developed by Hardie and Lucas (2002) for ACARP assessed the hydraulic and geomorphic performance of 35 undiverted, natural reaches of regional streams to identify key parameters that affect and dictate the shape and form of streams, forming the basis of criteria to be applied to diversion design and rehabilitation. These parameters are provided below in Table 1.

Stream type	Stream power		Velocity		Shear Stress	
	2-year ARI	50-year ARI	2-year ARI	50-year ARI	2-year ARI	50-year ARI
Incised	20–60	50–150	1.0–1.5	1.5–2.5	<40	<100
Limited capacity	<60	<100	0.5–1.1	0.9–1.5	<40	<50
Bedrock controlled	50–100	100–350	1.3–1.8	2.0–3.0	<55	<120

Note: the two- and 50-year average recurrence interval (ARI) events are equivalent to the 39 per cent and two per cent annual exceedance probability events respectively.

TABLE 1 – Typical values for dependent variables identified for sample stream reaches in the Bowen Basin, Queensland (from Hardie and Lucas, 2002) in the Bowen Basin, Queensland (from Hardie and Lucas, 2002).

Stream type	Sediment transport group	Stream power (W/m2)	
		2-year ARI	50-year ARI
Alluvial	Supply limited (low sediment supply)	15–35	50–100
	Transport limited (high sediment supply)	35–60	80–150
Prevalent bedrock controls	n/a	50–100	100–350

Note: the two- and 50-year average recurrence interval (ARI) events are equivalent to the 39 per cent and two per cent annual exceedance probability events respectively.

TABLE 2 – Mean reach stream power identified for sample stream reaches in the Bowen Basin, Queensland (Alluvium, 2014).

More recent criteria for functioning river landscape units in mining and post mining landscapes were developed by Alluvium (2014) for ACARP by reanalysing the data set developed and assessed for the 2002 ACARP project (Hardie and Lucas, 2002). The criteria included alluvial channel design parameters presented in Table 2 based on systems with high and low sediment supply.

It is recognised that the design parameters in Table 1 and 2 are not directly applicable to the design of creek diversions in the Pilbara region of Western Australia as they do not adequately capture the region's unique hydrological and geomorphological conditions. For this reason the design approach generally adopted in Western Australia is focused on completing detailed assessment, modelling and characterisation of the existing creek system and the proposed diversion to demonstrate that the hydraulic, ecological and geomorphological values of the diversion match the conditions in the existing creek (Department of Resources, Energy and Tourism, 2008).

An integrated approach to design

A key challenge when developing diversion designs that function in a similar way to the existing system is the need to understand the inter-related nature of hydrology, hydraulics, geomorphology, sediment transport, hydrogeology, aquatic ecology, riparian vegetation and capture these processes in the geotechnical and civil design (Figure 5).

For example, the diversion widths and bed gradients influence the key hydraulic parameters, and in turn the sediment transport regime, the geomorphology of the creek, what types of vegetation may establish and what vegetation types may survive large flood events.

Similarly, the volume and composition of alluvium in the diversion will dictate the sub-surface water flows and water availability needed to sustain vegetation types and densities. The diversion design needs to allow for scour/erosion to occur during flood events that is consistent with the existing system and it also needs to allow for geomorphic processes to occur over time, such as the lateral movement of the low flow channels.

The flood protection bunds/levees are designed based on geotechnical data and analysis, but the design must also consider the hydraulics of the creek and potential scour depths at the toes of the bund. The geomorphology of the creek also needs to be considered – closure designs must consider the long-term evolution of the diversion and how future scenarios may affect the design. The density of vegetation also affects channel roughness, which in turn influences flood levels and bund heights.

All of these complex interactions need to be well understood, based on the analysis of the natural creek system and used to inform the diversion design. The most effective way to capture these interactions and address all potential risks associated with the design and construction of Pilbara creek diversions is through the use of an integrated team of specialists covering each discipline working closely with the mine planning team.

Design for operations with consideration of closure

Operational diversion designs pay less attention to short-term environmental outcomes, but aim to maximise operational requirements during the operating life of the mine (Markham, 2012; Markham, Atkinson and Pearson, in press). This phase requires a design that incorporates critical ecosystem components (e.g. organism passage) and would be complimentary to longer term environmental objectives, but might include a greater use of engineered structures to achieve hydraulic objectives and to ensure a greater degree of predictability. Diversions and associated flood protection bunds/levees are generally designed to provide protection (with freeboard) during the one per cent AEP design storm event. Mine sites with shorter/longer design lives may consider alternative design AEPs using a risk-based approach. Within this phase, it is also important to balance the need to show the regulators that despite the greater use of engineered structures, the diversion is on a trajectory towards equilibrium to demonstrate long-term self-sustenance (Markham, Atkinson and Pearson, in press).

Closure designs involve further creek rehabilitation works once the diversion has finished functioning as an operational structure. The final landform design at closure, including the diversions, must be designed to function effectively during more extreme events in excess of the one per cent AEP. The specifications associated with the closure design may differ from the operational phase, and could incur significant additional cost to implement. It is recommended that material won from diversion construction is also considered for use at closure where appropriate. This is particularly the case where suitable quantities of competent rock amour are in short supply.

So although minimising earthworks is an effective way to reduce upfront capex when designing operational diversions, failure to consider the diversion performance under closure conditions may have significant cost implications which could outweigh the short-term benefits.

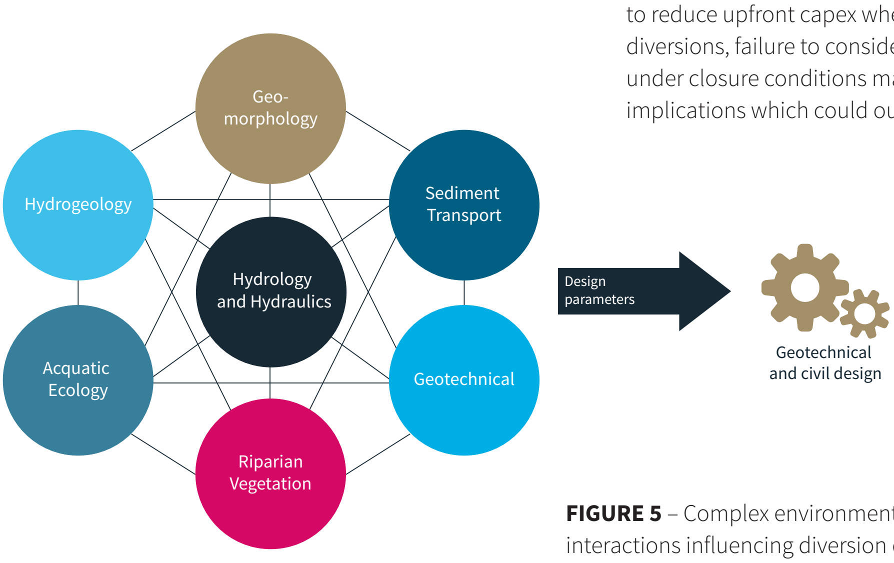


FIGURE 5 – Complex environmental interactions influencing diversion design.

Modelling of extreme events in excess of the one per cent AEP is required to demonstrate that the diversions and any associated flood bunds/levees can remain stable following mine closure.

These cost implications may include:

- Cost of having to remobilise earthworks contractors to modify the diversion and flood bund designs until the hydraulics and sediment transport characteristics are similar to the existing case and can support the reestablishment of riparian vegetation and associated ecosystems. There is also the risk that suitable material needed to amend the designs for closure may not be available once mining has finished so may need to be sourced from elsewhere at significant cost.
- Cost associated with ongoing maintenance. From a regulatory perspective, this is an important consideration for relinquishment at the end of mine life, where an inappropriate design would likely lead to ongoing channel instability and ongoing maintenance costs.

If the costs associated with closure for each of the options are included in the option analysis described earlier, then this may have the potential to influence decision-making.

Some of the design considerations for closure that should be addressed when developing diversion designs include:

- Revegetation of the diversion over time will stabilise banks following mine closure. The revegetation will also increase channel roughness and affect the hydraulic behaviour in the diversions, which needs to be explored and understood to mitigate risk.
- Modelling of extreme events in excess of the one per cent AEP is required to demonstrate that the diversions and any associated flood bunds/levees can remain stable following mine closure. A diversion sized to convey the one per cent AEP event may not have sufficient capacity to convey more extreme flood events which could lead to ongoing channel instability and ongoing maintenance costs (i.e. failure to relinquish).
- Assumptions associated with the size and type of rock needed to protect diversions and flood bunds/levees from erosion and failure during extreme events following mine closure should be supported with geotechnical field work and testing.
- Spillways may be required at closure to pass extreme flood events in excess of the one per cent AEP flood event through pit voids in a safe and controlled manner without impacting on the long-term stability of the final closure landform design. The spill crest level and spillway geometry will influence the flows and hydraulic behaviour which should be assessed to confirm the performance of the closure design. Significant work is needed to confirm the feasibility of the spillway concept, including availability of suitable material to construct spillways, structural integrity, stability analysis, cumulative impacts on flow downstream and sediment transport.

Conclusions

Over recent years there has been a significant increase in the number of miners in the Pilbara region of Western Australia targeting CID located in valleys, intersected by ephemeral creeks and below the groundwater table. The falling iron ore price over recent years has triggered a drive to reduce cost and maximise yield. Creek diversions provide an opportunity to maximise the utilisation of orebodies and extend the life of mine. This resilience gained through the use of creek diversions can only be successfully achieved through careful consideration of the balance between operational and closure design requirements, the complex inter-related nature of hydrology, hydraulics, geomorphology, sediment transport, hydrogeology, aquatic ecology, riparian vegetation and the importance of capturing these processes in the geotechnical and civil design.

The design of major Pilbara creek diversions is more complex as they are usually required to function in a similar way to the existing creek system during operations and remain stable during more extreme events following mine closure, in accordance with current regulatory guidance.

Although potentially a complex process, the potential return on investment gained through the use of diversions can be significant, so a well-structured methodology should be developed and implemented to allow the costs of all potential diversion options to be assessed and compared early in the mine planning phase. This must also include consideration of the associated environmental and social risks/costs, which can have a significant bearing on diversion decision making.

However, with sound engineering design and risk management processes in place the likelihood of these risks occurring can be minimised. Analysis of typical CID-creek ore intersections in the Pilbara region suggests that the value of ore potentially recovered through the use of diversions could be in the order of hundreds of millions, possibly billions of dollars per diversion depending on market conditions. Therefore, it would be prudent to fully explore the business case for diverting creeks to mine creek ore. While there are several technical, operational and environmental risks to be managed, with appropriate engineering design and risk management processes in place, the significant financial benefits of diversions can be realised.

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