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Room for rivers in mining landscapes: implications for mine closure design

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Abstract

Mines interact with rivers in numerous ways. This paper is interested in their long-term physical interactions, especially as mines close. Mine closure planning requires practitioners to assess river behaviour over timescales extending well beyond conventional engineering design horizons, while landscape evolution models (LEMs) are increasingly used to evaluate long-term erosion and sediment generation from rehabilitated landforms, usually in small streams in the headwaters. Less attention is given to the capacity of larger channels and downstream floodplains to adjust to changing hydrological and sediment regimes over equivalent timescales. Consequently, closure assessments may underestimate risks associated with channel migration, avulsion, incision, aggradation and floodplain reworking where these processes interact with residual mine landforms such as final voids, waste rock dumps and tailings storage facilities.

Internationally, the Room for Rivers (RfR) and Freedom Space concepts recognise that rivers require sufficient corridor width to accommodate geomorphic adjustment while maintaining long-term resilience. Although these concepts are increasingly incorporated into river management, it is proposed here that they could be highly useful, potentially even essential, in mine closure planning.

Keywords: *mine closure, Room for Rivers, Freedom Space, geomorphology, river diversion*

1 Introduction

Mine closure requires confidence that rehabilitated landscapes will remain physically stable and environmentally acceptable over timescales extending hundreds to thousands of years. For mining operations located adjacent to rivers, achieving this confidence is particularly challenging because river systems are inherently dynamic. Unlike engineered infrastructure designed to remain fixed, rivers continuously adjust their geometry, sediment regime and floodplain configuration in response to changing hydrological, climatic and catchment conditions. Over closure timescales, these processes may fundamentally alter the interaction between waterways and residual mine landforms.

Conventional mine closure assessments frequently evaluate the condition of individual landform domains independently. Landscape evolution models are routinely applied to assess long-term erosion and sediment generation from rehabilitated slopes, while hydraulic modelling is used to evaluate flood behaviour over selected design events. However, these approaches often provide limited consideration of the longer-term geomorphic adjustment of valley-floor channels and floodplains. As a consequence, closure assessments may not adequately evaluate whether channel migration, avulsion, aggradation or incision could create future interactions with residual voids, waste rock dumps, tailings storage facilities or other critical closure receptors. This distinction is particularly important because a channel exhibiting ‘very good’ geomorphic condition at the time of assessment and application for relinquishment may nevertheless be unsuitable for relinquishment if its future adjustment pathways present unacceptable risks.

The concept of Room for Rivers (RfR) (Rijke et al. 2012; Warner et al. 2013) has emerged internationally as an alternative to traditional river management approaches that sought to constrain rivers within fixed

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alignments through levees, bank protection and channel stabilisation. Rather than resisting geomorphic processes, RfR recognises that rivers require sufficient corridor dimensions to accommodate floodplain inundation, channel migration, sediment redistribution and ecological processes. Closely related concepts, including the Canadian Freedom Space framework (Biron et al. 2014), similarly define the spatial envelope within which rivers are expected to adjust over time and encourage land use planning that accommodates, rather than suppresses or seeks to control, natural geomorphic behaviour.

Despite the growing adoption of these concepts within river management's remit, their application to mine closure remains limited. Mining landscapes differ from most catchments because they frequently contain high cost-and-consequence features that cannot tolerate unrestricted river adjustment. Final voids, waste rock dumps, tailings storage facilities and contaminated materials often impose physical constraints on river corridors that are uncommon in non-mining environments. Closure planning therefore requires not only an understanding of how rivers are likely to adjust, but also whether sufficient space exists for those adjustments to occur without compromising closure objectives or creating unacceptable long-term liabilities.

This paper positions RfR as a closure planning framework rather than a river management philosophy. Building upon Australian experience in watercourse diversion design, including Australian Coal Association Research Program (ACARP) Project C20017 (Alluvium 2014) and C23030 (White et al. 2015), it proposes a trajectory-based approach to evaluating river behaviour over closure timescales. The central proposition advanced is that closure suitability should be distinguished from current geomorphic condition. While a natural or diverted watercourse may function well under present conditions, closure decisions should be based on whether future geomorphic adjustment can occur without unacceptable interaction with residual mine landforms. By integrating concepts of long-term catchment and watercourse trajectories, sediment budgets, landscape evolution modelling, event-scale fluvial modelling and program logic, the paper demonstrates how RfR thinking can strengthen the technical defensibility of closure assessments and provide a more robust basis for long-term relinquishment.

2 Defining 'Room for Rivers'

The concept of RfR represents a fundamental shift in river management philosophy. Historically, rivers were managed by constraining their lateral and vertical adjustment through levees, bank protection, channel realignment and flood control infrastructure. These approaches sought to minimise inundation and protect adjacent assets by maintaining a fixed channel alignment. While often successful over relatively short engineering design lives, they frequently transferred geomorphic processes elsewhere within the catchment, reducing river resilience and increasing long-term maintenance requirements.

Internationally, river management has increasingly recognised that rivers are dynamic systems requiring sufficient space to adjust naturally in response to variations in water discharge, sediment supply, vegetation succession and climatic variability. The RfR concept is most closely associated with the Dutch national Room for the River program, which reframed flood-risk management from constraining rivers between progressively higher defences towards creating space for inundation, conveyance and riverine processes ([Rijkswaterstaat n.d.; Warner et al. 2013] and refer the review of this large Dutch government program by van Alphen [2016] or Zevenbergen et al. [2015]). Similarly, the Canadian concept of Freedom Space defines the corridor within which channel migration and floodplain adjustment are expected to occur over management timescales and provides a framework for spatial planning that accommodates, rather than constrains, geomorphic processes (Biron et al. 2014).

Importantly, RfR extends beyond conventional floodplain management. Flood studies traditionally focus on the probability and consequences of inundation associated with specified design events. RfR recognises that long-term river behaviour is governed by a broader suite of interacting geomorphic processes including:

- lateral channel migration
- meander development and cut-off formation
- avulsion

- bank erosion
- bar formation and reworking
- floodplain sedimentation
- channel incision
- vegetation succession and disturbance
- sediment dynamics throughout the catchment.

Collectively, these processes define the spatial envelope required for rivers to remain resilient while continuing to adjust to changing boundary conditions. Rather than attempting to preserve a particular channel form, RfR seeks to maintain the capacity of river systems to recover following disturbance while accommodating natural variability.

For mine closure planning, this distinction is particularly important. Closure assessments extend over timescales during which geomorphic adjustment is inevitable. Consequently, the relevant question is not whether a river will change, but whether sufficient space exists for that change to occur without creating unacceptable interactions with residual mine landforms or compromising closure objectives.

In Canada this approach is called Freedom Space and it predicts a risk probability zone in which the river is likely to flood and migrate (Biron et.al. 2014 and Figure 1). This represents a shift from attempting to maintain fixed channel geometry to explicitly accommodating system variability (Table 1).

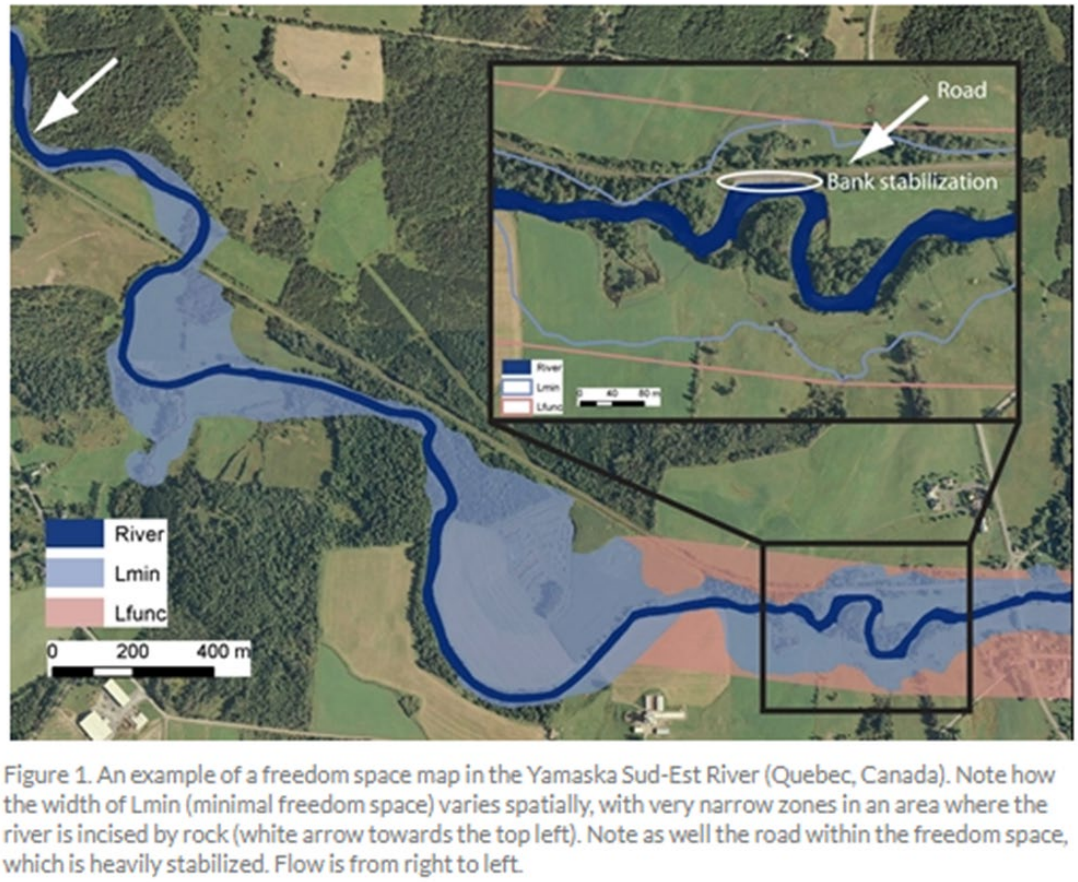

Figure 1 Example of a Freedom Space map for the Yamaska Sud-Est River in Canada (Biron et al. 2014)

Table 1 Conceptual shift from conventional river management to Room for Rivers thinking

Traditional approach	Room for Rivers approach
Fixed channel alignment	Allowance for channel adjustment
Flood conveyance	Geomorphic process accommodation
Structural stability	System resilience
Local asset protection	Catchment-scale risk management
Static design condition	Dynamic recovery trajectories
Short engineering design life	Long-term landscape evolution
Channel stability	Functional river behaviour

3 Why mining landscapes are different

Although RfR principles are increasingly applied within natural catchments, their implementation within mining landscapes is substantially more complex because rivers frequently coexist with landforms that cannot tolerate unrestricted geomorphic adjustment.

Unlike agricultural or urban floodplains, mining landscapes commonly contain residual mine features whose long-term integrity is fundamental to successful closure and relinquishment. These include final voids, waste rock dumps, tailings storage facilities, engineered flood protection structures and rehabilitated landforms. Consequently, closure planning must simultaneously accommodate natural river adjustment while ensuring that geomorphic processes do not compromise critical closure infrastructure.

Several closure risk pathways arise where rivers are constrained or where insufficient adjustment space exists.

The most obvious is lateral channel migration into final voids or rehabilitated waste rock dumps. Although channel migration is a natural process within alluvial systems, interaction with these landforms may result in accelerated erosion, exposure of reactive materials, increased sediment generation, loss of downstream ecosystem function or unacceptable public safety risks.

Similarly, lateral erosion into tailings storage facilities or containment structures may expose stored materials to fluvial processes, increasing the likelihood of contaminant mobilisation and long-term environmental liability.

Vertical adjustment also presents significant risks. Reduced sediment inputs when catchments have adjusted to altered land use and started to recover may promote channel incision; undermining rehabilitated floodplain surfaces and altering groundwater connectivity. Conversely, excessive sediment delivery from existing or new phases of catchment erosion may lead to aggradation, reducing channel conveyance and increasing the likelihood of avulsion into previously unaffected areas.

These risks are further complicated by evidence that many river systems exhibit non-stationary (Milly et al. 2008) behaviour over geological and historical timescales. River terraces preserved throughout many Australian catchments indicate that flood regimes and sediment transport processes have varied substantially over time, demonstrating that the instrumental hydrological record alone is unlikely to represent the full range of future geomorphic behaviour. Projected changes in rainfall intensity under a changing climate further reinforce the need to consider a broader envelope of plausible future adjustment.

Mine closure therefore requires a fundamentally different planning perspective from conventional engineering design. Rather than seeking to eliminate geomorphic change, closure assessments should evaluate whether foreseeable adjustment processes can occur without compromising closure objectives or creating unacceptable long-term liabilities.

4 Gaps in current practice

Current mine closure assessments frequently adopt a domain-based approach in which rehabilitated slopes and minor drainage lines, floodplains and watercourses are evaluated independently. Although this approach has proven valuable for understanding individual landform performance, it can obscure the interconnected nature of sediment generation, sediment transport and downstream channel adjustment.

Landscape evolution models are routinely used to estimate long-term erosion and sediment generation from rehabilitated slopes. These predictions commonly form an important component of closure assessments. However, comparatively less emphasis is often placed on evaluating how downstream watercourses and floodplains respond to those evolving sediment inputs over equivalent timescales. Similarly, hydraulic modelling typically focuses on flood behaviour associated with selected design events rather than long-term geomorphic adjustment.

This disconnect introduces uncertainty into closure decision-making. A rehabilitated landform may satisfy erosion performance objectives while simultaneously generating sediment regimes capable of initiating downstream channel migration, incision or aggradation. Conversely, apparently stable river reaches may remain susceptible to future adjustment where catchment sediment supply, vegetation dynamics or hydrological regimes evolve beyond those represented in current models.

The practical implication is that closure assessments based solely on present geomorphic condition or isolated landform performance may underestimate future interactions between rivers and residual mine landforms and infrastructure. Consequently, closure suitability cannot be inferred solely from current condition. Rather, it should be evaluated in terms of future geomorphic trajectories and the consequences should those trajectories intersect residual mine landforms.

Adopting a whole-of-catchment perspective, analogous to integrated catchment management, provides a more defensible basis for closure planning. Such an approach explicitly links sediment generation, sediment transport, channel adjustment and receptor sensitivity, thereby allowing closure risks to be evaluated at landscape scale rather than within individual domains.

5 ACARP C20017 as the bridge between river management and closure planning

Although developed primarily for the design and assessment of mine watercourse diversions, ACARP Project C20017 provides many of the conceptual elements required to apply RfR thinking to mine closure.

The project recognised that successful watercourse diversions should not be evaluated solely by reference to channel stability. Instead, performance should be assessed according to whether geomorphic processes remain consistent with the intended design philosophy. Consequently, the guidance distinguishes between threshold channels, where erosion must remain limited because of nearby infrastructure, and alluvial channels, where geomorphic adjustment within reasonable bounds forms part of the intended system behaviour.

This distinction aligns closely with international RfR principles. Rather than requiring channels to remain fixed indefinitely, the emphasis shifts towards understanding the range of adjustment considered acceptable within the design corridor.

The program logic framework embedded within ACARP C20017 further strengthens this perspective by explicitly linking investigation, design assumptions, construction quality, monitoring, disturbance response and long-term performance. Importantly, it recognises that successful river systems are characterised by recovery following disturbance rather than the complete absence of disturbance.

Viewed through a closure lens, this framework extends naturally beyond diversion design. Closure assessments should similarly evaluate whether rivers can continue to function following future floods, sediment pulses or vegetation change without creating unacceptable interactions with residual mine landforms. This represents the critical transition from evaluating current geomorphic condition towards evaluating future system trajectories and provides the conceptual bridge between established river management practice and long-term mine closure assessment.

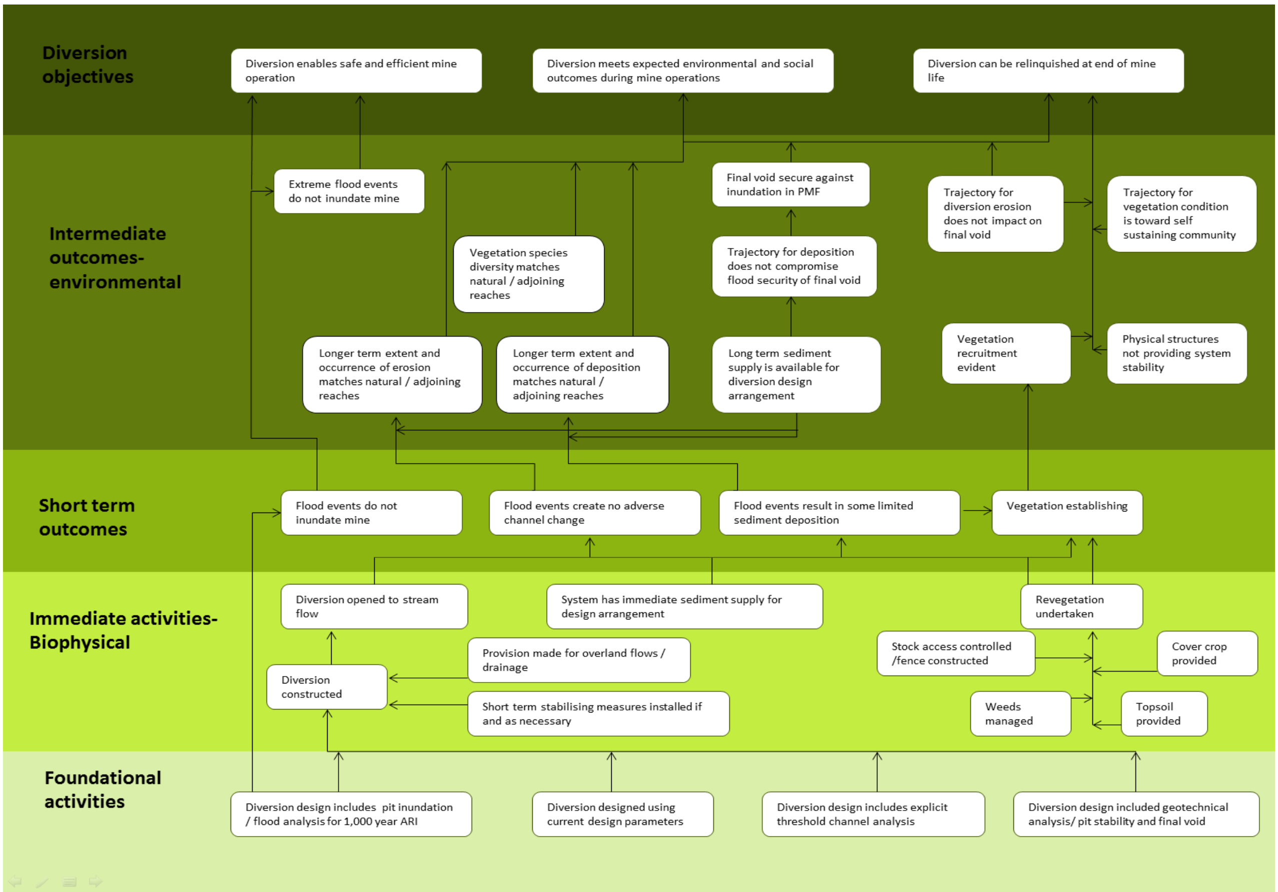

Figure 2 Program logic approach to diversion design (ACARP C20017)

6 Applying Room for Rivers concepts to mining landscapes

6.1 Watercourse diversions

Watercourse diversions provide the clearest opportunity to apply RfR principles within mining landscapes because the design objectives, corridor geometry and long-term performance expectations are explicitly defined during mine development. Over the past 3 decades, diversion design in Australia has evolved from relatively simple channel excavation approaches towards process-based designs that recognise sediment continuity, geomorphic adjustment and long-term resilience. This progression has been supported by research undertaken through ACARP Project C20017 and C23030 and subsequent industry experience (Lucas 2025).

Historically, many diversions were designed with the intent to remain geometrically stable under nominated design events. Although these approaches frequently achieved satisfactory hydraulic performance in the short term, they often underestimated the influence of evolving sediment regimes, vegetation establishment and natural geomorphic adjustment. The consequence is that apparent stability during the operational phase does not necessarily translate into confidence regarding long-term closure performance.

Contemporary diversion design increasingly distinguishes between threshold channels, where infrastructure proximity requires limited adjustment, and alluvial channels, where erosion and deposition within certain limits are recognised as normal and desirable components of system behaviour. The diversion illustrated in Figure 3 represents this latter philosophy. Although measurable erosion and deposition have occurred since construction (Figure 4), these adjustments are consistent with the intended design behaviour rather than evidence of failure. Such performance illustrates an important principle of RfR: successful systems should be evaluated according to whether geomorphic processes remain within acceptable behavioural limits rather than whether channel geometry remains unchanged.

Nevertheless, even well-performing diversions remain subject to uncertainty associated with changing catchment conditions, vegetation succession and future climatic variability. Consequently, diversion performance should be interpreted within a broader closure context that considers not only the present condition but also the consequences should future adjustment exceed the intended design envelope.

Figure 3 Recently constructed diversion exhibiting alluvial low-flow channel performance developing morphologic heterogeneity within a threshold high-flow channel in close proximity to an open cut pit

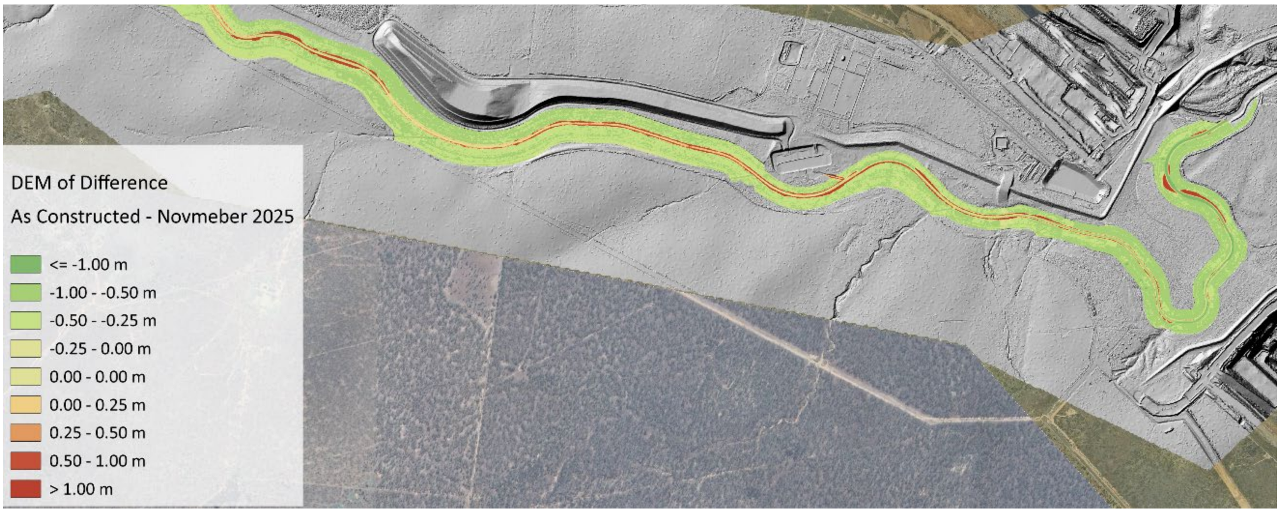

Figure 4 Digital elevation model of difference for the recently constructed diversion, exhibiting erosion and deposition as expected within the design paradigm for an alluvial low-flow channel

6.2 Natural watercourse corridors

Application of RfR principles becomes considerably more challenging where natural watercourses remain adjacent to mine infrastructure. Unlike constructed diversions, natural channels possess adjustment pathways that are largely independent of mine design assumptions. Consequently, maintaining current channel alignment cannot generally be assumed over closure timescales.

Figure 5 illustrates an alluvial river immediately adjacent to an open cut mine pit. Although the channel currently occupies a relatively stable alignment, its alluvial boundaries indicate an inherent capacity for future migration through the combined influence of bank erosion, vegetation dynamics, sediment transport and floodplain adjustment. The proximity of the mining landform substantially limits the available corridor within which these natural processes can occur.

Under these circumstances, the central closure question is not whether channel adjustment will occur, but whether the available adjustment space is sufficient to prevent unacceptable consequences.

Where corridor constraints are identified, several management responses may be considered during closure planning. These include increasing setbacks between rivers and final landforms, redesigning rehabilitated landforms to provide wider adjustment corridors, relocating or removing infrastructure where practicable, or identifying residual risks requiring long-term monitoring and management. Selection among these alternatives should be informed by an assessment of geomorphic processes, receptor sensitivity and the likelihood of future channel adjustment rather than current channel condition alone.

Figure 5 Low sinuosity alluvial channel directly adjacent to an open cut mine pit, illustrating the lack of potential for adjustment without severe consequences

6.3 Closure suitability: beyond the 'very good' condition paradigm

One of the central propositions of this paper is that current geomorphic condition and closure suitability should not be regarded as equivalent concepts.

Diversions designed in accordance with contemporary best practice frequently achieve a 'very good' geomorphic condition grade when assessed against established assessment frameworks. The diversion shown in Figures 6 and 7 provides an example of such performance. After approximately 2 decades of operation, the diversion exhibits positive trajectory vegetation, a regionally prevalent array of geomorphic units and behaviour consistent with its intended design philosophy.

From an operational perspective, these characteristics provide strong evidence of successful diversion performance. However, closure planning requires a broader assessment.

The critical question is not whether the diversion functions well today but whether future geomorphic adjustment could occur without creating unacceptable interactions with adjacent mine landforms. Where threshold channels occur immediately adjacent to final voids, waste rock dumps or other high-consequence receptors, even relatively modest planform migration may have consequences disproportionate to the magnitude of the geomorphic adjustment itself.

Accordingly, closure suitability should be assessed using a trajectory-based framework that explicitly considers:

- anticipated channel adjustment pathways
- disturbance and recovery processes
- changing sediment supply
- potential future climatic variability
- sensitivity of adjacent closure receptors
- consequences should predicted adjustment occur.

This represents a fundamental shift in closure assessment philosophy. Rather than asking whether the river is currently stable, practitioners should evaluate whether future geomorphic behaviour remains compatible with closure objectives over the timescales required for relinquishment.

Figure 6 Diversion designed and constructed to the ACARP C20017 Standard, now 20 years old and in 'very good' condition

Figure 7 Aerial view of the 'very good' condition diversion in Figure 6, illustrating proximity to mining pits and dumps and the potential consequence of any channel migration

7 Consequences of constraining river adjustment

Where rivers are prevented from adjusting naturally, geomorphic processes are rarely eliminated; instead, they are transferred spatially or temporally within the river system. Consequently, closure risks may emerge many years after apparent completion of rehabilitation works.

Experience from diversion performance studies (Alluvium 2014; Lucas 2025) has demonstrated several recurring pathways through which constrained river systems may generate long-term closure risks.

Interruptions to sediment continuity may promote either channel incision, where sediment supply becomes deficient, or aggradation, where sediment supply exceeds transport capacity. Both processes alter channel geometry, floodplain connectivity and hydraulic behaviour, potentially increasing the likelihood of future adjustment.

Similarly, lateral migration constrained by adjacent infrastructure may increase local bank erosion rates or redirect adjustment towards more vulnerable locations. Where channel and floodplain elevations vary relative to each other through aggradation, the likelihood of avulsion may increase, creating entirely new flow paths beyond those considered during original closure planning.

The practical implication is that apparent geomorphic stability observed over operational timescales should not be interpreted as evidence of long-term closure performance. Instead, closure assessments should explicitly evaluate the consequences associated with plausible future adjustment scenarios and determine whether sufficient room exists for those adjustments to occur without compromising closure objectives.

8 Integrating landscape evolution modelling and event-scale fluvial modelling

8.1 Why integration matters

Mine closure modelling commonly separates long-term landscape evolution from river adjustment processes. Although this division reflects the strengths of individual modelling tools, it introduces uncertainty when evaluating long-term closure performance because sediment generation, sediment transport and channel adjustment are fundamentally interconnected.

Landscape evolution models provide valuable predictions of long-term erosion, landform evolution and sediment production. However, they generally do not explicitly simulate valley-floor channel migration, bar dynamics or floodplain evolution. Conversely, hydraulic and morphodynamic models are capable of representing event-scale channel behaviour but are rarely applied over closure-relevant timescales.

Consequently, closure assessments may successfully quantify sediment generation while providing comparatively limited understanding of how receiving river systems respond to those changing sediment inputs. The principal consequence is increased uncertainty regarding future interactions between rivers and critical closure receptors.

Table 2 Relative capabilities of commonly applied modelling approaches

Modelling approach	Principal strengths	Principal limitations
Landscape evolution models	Long-term erosion, sediment generation, landform evolution	Limited representation of long-term channel and floodplain evolution
Hydraulic models	Flood hydraulics, inundation mapping and flow distribution	Limited prediction of geomorphic adjustment
Morphodynamic models	Event-scale erosion, deposition and channel adjustment	Computationally intensive and generally limited to shorter simulation periods

8.2 A trajectory-based modelling framework

Rather than treating these modelling approaches independently, they can be integrated within a program logic framework that supports closure decision-making.

The proposed workflow comprises 6 sequential steps:

1. Define closure objectives and identify critical receptors.
2. Characterise channel type and likely adjustment mechanisms.
3. Quantify long-term sediment supply using landscape evolution modelling.
4. Delineate the RfR corridor by combining flood behaviour with anticipated geomorphic adjustment.
5. Apply event-scale hydraulic or morphodynamic modelling to evaluate river behaviour within the proposed corridor under representative disturbance scenarios.
6. Evaluate predicted trajectories against closure objectives, monitoring requirements and completion criteria.

Within this framework, landscape evolution modelling defines the evolving boundary conditions under which river adjustment occurs, while event-scale modelling evaluates how rivers respond to those changing conditions. Together, these approaches provide a more defensible basis for determining whether sufficient adjustment space exists to accommodate future geomorphic processes without compromising adjacent mine landforms.

Importantly, the objective is not to predict a single future channel alignment. Rather, the objective is to define the range of plausible adjustment pathways and evaluate whether those pathways remain compatible with long-term closure objectives.

Figure 8 conceptually illustrates this integrated modelling framework. It demonstrates how sediment supply predicted through landscape evolution modelling informs subsequent event-scale assessment of channel behaviour, with both modelling approaches linked through program logic to closure decision-making, monitoring and eventual relinquishment.

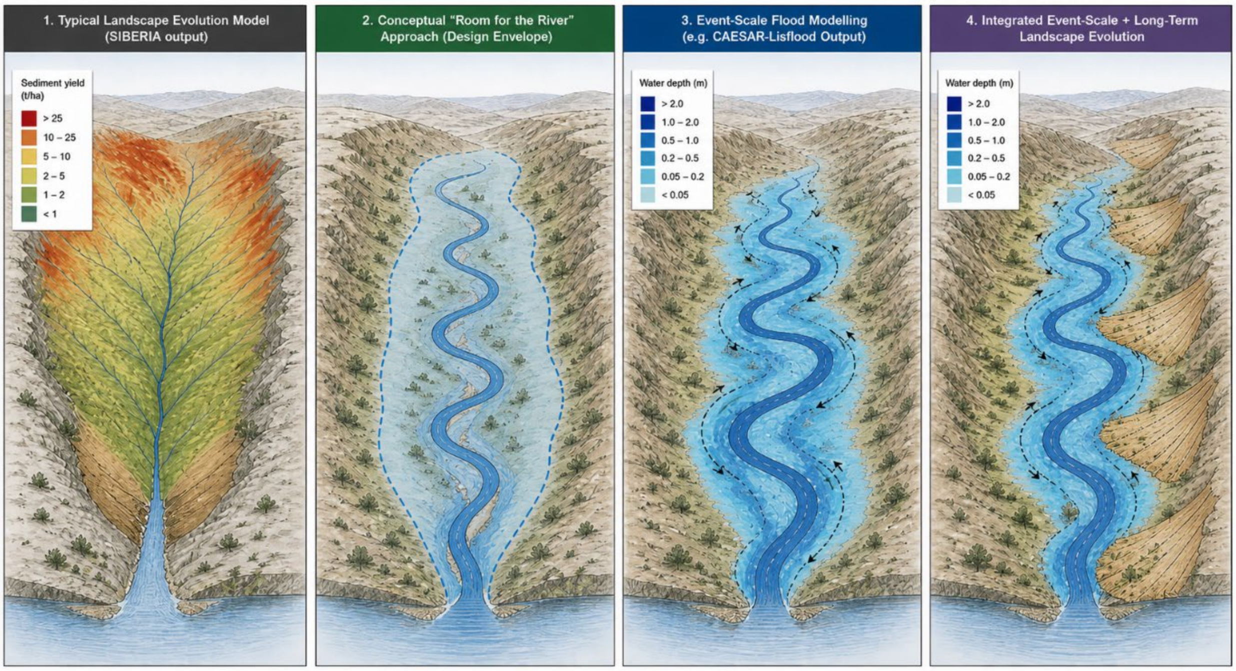

Figure 8 Conceptual integration of long-term landscape evolution modelling (LEM) and event-scale fluvial modelling within a Room for Rivers framework. Note that LEM outputs are used here to represent long-term erosion and sediment supply; valley-floor channel processes are represented through event-scale modelling and corridor-based assessment

9 Conclusion

Mine closure planning differs fundamentally from conventional river engineering because it requires practitioners to evaluate river behaviour over timescales extending well beyond those traditionally considered in engineering design. Over these timescales, channel migration, avulsion, floodplain reworking, and changing sediment and hydrologic regimes should be regarded as expected components of river evolution rather than exceptional events. Consequently, closure assessments that rely primarily on current geomorphic condition provide only a partial basis for evaluating long-term closure performance.

The international Room for Rivers (RfR) and Freedom Space concepts provide an established framework for recognising that rivers require sufficient corridor width to accommodate geomorphic adjustment while maintaining resilience. Although these concepts are now widely recognised in river management, their application within mine closure has remained comparatively limited despite the long-term interaction between rivers and residual mine landforms representing one of the principal uncertainties affecting relinquishment.

This paper has argued that the principal distinction for mine closure is between the current geomorphic condition and closure suitability. A river diversion or natural channel may exhibit a 'very good' geomorphic condition under present conditions while still presenting unacceptable long-term closure risk if future adjustment pathways intersect final voids, waste rock dumps, tailings storage facilities or other high-consequence receptors. Accordingly, closure assessments should shift from evaluating whether river systems are currently stable towards evaluating whether future geomorphic trajectories remain compatible with closure objectives.

Application of RfR principles provides a practical mechanism for making this transition. By explicitly identifying the spatial envelope required for channel adjustment, integrating catchment sediment budgets with river corridor assessment, and linking landscape evolution modelling with event-scale fluvial modelling through a program logic framework, practitioners can evaluate not only how rivers are likely to evolve but also the consequences should those adjustments occur. This trajectory-based approach provides a stronger technical basis for evaluating uncertainty than assessments founded solely on present-day condition.

The practical implication for mine closure is that river corridors should become a fundamental design consideration rather than a secondary assessment following landform design. Delineation of adjustment corridors, identification of closure receptors, assessment of geomorphic consequence pathways and integration of long-term modelling should become routine components of closure planning where rivers interact with mine infrastructure. Such an approach supports an increasingly transparent evaluation of residual risk, more defensible completion criteria and improved confidence in eventual relinquishment.

Rather than representing a new river management philosophy, the application of RfR principles to mine closure extends established geomorphic thinking into the closure domain. In doing so it provides a practical framework for incorporating long-term river adjustment into closure design, strengthening the scientific defensibility of closure decisions and improving confidence that post-mining landscapes will remain functional without unacceptable environmental or maintenance liabilities.

Use of artificial intelligence disclosure statement

In the preparation of this work the author used ChatGPT to generate Figure 8. The author has reviewed the content and edited it where required, and takes full responsibility for said content.

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