Three models walk into a pool: A process-based, multi-method framework for understanding dryland pool sediment dynamics

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Key points

- Dryland pool habitats are critical dry-season refugia whose persistence depends on flow and sediment regimes, yet their dryland behaviour cannot be reliably characterised by conventional single-metric assessments.
- A multi-method, process-based framework was developed that integrates stochastic long-term sediment yield modelling, event-based sediment delivery modelling, and event-scale hydraulic flushing assessment, synthesised through a conceptual sediment flux balance.
- Applied to a Pilbara mine expansion where the persistence of pool habitat is critical, the framework resolved cumulative trends, event-driven behaviours, and the supply–removal balance within pools, yielding diagnostic depth not achievable through conventional approaches.
- The framework supports defensible, semi-quantitative impact assessment by identifying pools at risk geomorphic change, articulating mechanisms of change, and guiding targeted monitoring and mitigation, and is transferable to any dryland system subject to catchment reconfiguration.

Abstract

Pool habitats in dryland river systems are highly sensitive to changes in flow and sediment regimes, yet predicting their response to catchment disturbance remains a challenge for impact assessment and management and requires approaches that move beyond single-metric or event-scale assessments. This study applied a multi-method, process-based framework to evaluate sediment dynamics within pools subject to catchment area reductions associated with mine expansion in Western Australia.

The approach integrated three components:

1. Stochastic long-term sediment yield modelling using a Monte Carlo framework to characterise probabilistic sediment delivery.
2. Event-based sediment delivery modelling to resolve drivers of sediment flux across a range of flow magnitudes.
3. Event-scale flushing assessment, linking hydraulic modelling outputs with sediment mobility thresholds to quantify scour and transport across grain sizes.

These components were synthesised through a conceptual sediment balance model, resolving the interaction between delivery, transport, and in-pool storage of sediment.

This integration of various flow magnitudes and processes provided a level of diagnostic capability not typically achieved through conventional assessments, enabling cumulative trends and event-driven behaviours to be interrogated within a single framework. The approach supported a defensible, semi-quantitative evaluation of impact likelihood and severity grounded in physical process representation.

By resolving how sediment systems reorganise under altered boundary conditions, this methodology provided a robust basis for anticipating and managing processes in changing dryland river systems.

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Keywords

Dryland rivers, pool habitats, sediment dynamics, sediment flux balance, Monte Carlo modelling, flushing assessment, mine impact assessment, Pilbara

Introduction

Pool habitats represent critical ecological assets within dryland river systems. In landscapes where surface water is ephemeral and patchy, residual pools serve as critical dry season refugia for aquatic fauna and as colonisation sources when flows resume (Larned et al., 2010; Datry et al., 2014; Pinder et al., 2010). In the Pilbara region of northwestern Western Australia, one of Australia's most significant mining provinces and a region of globally significant ecological character (Halse et al., 2014), this role is acute. These pools are largely ephemeral, representing one of the primary persistent aquatic habitats available to obligate aquatic organisms during the extended dry season (Pinder et al., 2010). They are frequently associated with groundwater-dependent riparian vegetation of high conservation value and cultural significance to Indigenous communities (Alaibakhsh et al., 2017).

The physical character of pools in dryland rivers is intimately coupled to their flow and sediment regimes. Sediment supply, transport, and in-pool storage collectively determine pool morphology (depth, substrate composition, and turbidity) which in turn govern the ecological conditions they provide (Wood & Armitage, 1997; Dewson et al., 2007). In systems where flow is episodic and geomorphic work is concentrated in infrequent, high-magnitude events, changes to catchment configuration can produce lasting reorganisation of pool sediment dynamics (Laronne & Reid, 1993; Tooth & Nanson, 2011), with potential consequences for the persistence and quality of pool habitats over timescales that exceed individual events.

Catchment disturbance associated with mine development represents a particularly important class of perturbation in the Pilbara context. Open-cut mining progressively excises contributing catchment area, reducing the delivery of water and sediment to downstream reaches and pools. This catchment area reduction may diminish the flow energy and sediment supply that sustain pool morphology and flushing behaviour. Understanding how this reconfiguration alters catchment boundary conditions and propagates through the system, from hillslope erosion through fluvial transport to in-pool deposition and scour, is fundamental to defensible impact assessment.

Current single-metric approaches (e.g., percentage change in catchment area or peak discharge), fail to capture the multi-process, multi-temporal nature of pool sediment dynamics. Sediment delivery to pools is driven by hillslope erosion, channel and gully processes, and their collective transport capacity; flushing behaviour within pools is governed by hydraulic thresholds that vary by sediment calibre and flow magnitude; and cumulative changes to pool morphology emerge from the interaction between these inputs and outputs across a spatial and temporal hierarchy of events (Fryirs et al. 2007; Fryirs & Brierley 2013; Wohl et al. 2019). No single metric or model adequately resolves this complexity.

This paper presents a multi-method, process-based framework developed to address this challenge in the context of mine expansion in the Pilbara. The framework integrates three complementary modelling components across temporal and process scales, synthesised through a conceptual sediment flux balance. The approach was applied to evaluate potential impacts on pool habitats in a waterway system subject to significant catchment contraction. The study demonstrates that such integration provides a level of diagnostic depth and defensibility not achievable through conventional single-model assessments, with clear implications for the practice of dryland river impact assessment and pool habitat management.

Multi-method framework

Conceptual basis

Sediment dynamics in dryland pools operate across at least three distinct process-temporal domains that conventional approaches tend to address in isolation. Long-term pool morphology reflects the cumulative interaction of sediment inputs and outputs manifest across many events and years: this is the domain of catchment-scale sediment budgets and yield models. Event-scale pool behaviour – the delivery of discrete sediment pulses from hillslopes and channels during specific storms – determines how that long-term, cumulative interaction sets the conditions for resultant impacts during rare versus frequent events. Finally, the flushing domain constitutes in-pool hydraulic conditions during events which determine whether delivered sediment is deposited, retained, transported downstream, or scoured from in-pool stores.

Meaningful impact assessment requires all three domains to be addressed because changes in catchment configuration can alter each in different and sometimes opposing ways (hence the need for a multi-method approach). For example, catchment contraction may reduce long-term sediment supply while simultaneously reducing hydraulic energy and flushing capacity; the net effect on pool sediment storage depends on the relative magnitude of these changes, which can only be resolved by integrating all three perspectives. The framework presented here operationalises this integration through three inter-linked models and a synthesising sediment flux balance (Figure 1).

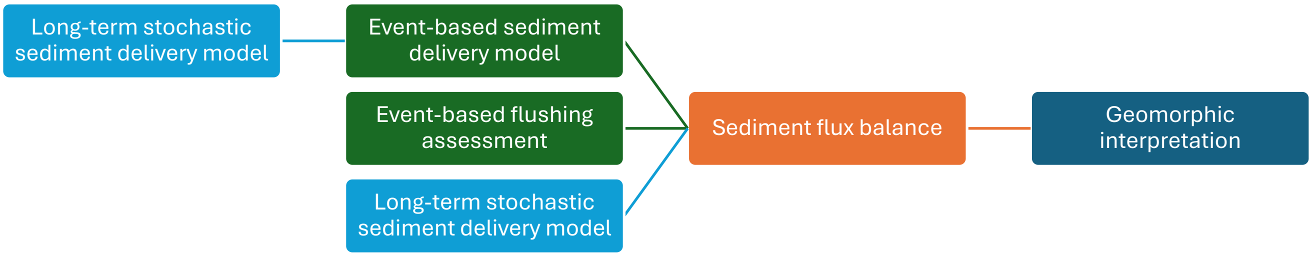

Figure 1 Structure of interrelations between components in assessment framework

Component 1: Long-term stochastic sediment delivery modelling

The long-term stochastic sediment delivery model (SSDM) characterises cumulative catchment sediment delivery over multi-year to decadal timescales under baseline and developed (post-mining) catchment conditions. A stochastic Monte Carlo (MC) framework was adopted, executing 100,000 simulations per scenario, to propagate uncertainty through all model inputs and generate probabilistic distributions of sediment delivery outcomes. This approach is critical in dryland systems, where the high inter-event and inter-annual variability of rainfall and runoff responses mean that single point estimates of sediment delivery are of limited value.

Catchment sediment supply (the volume of sediment mobilised within the catchment) was modelled as the sum of contributions from four erosion mechanisms:

$$CSS = HE + BE + BedE + GE$$

Where HE is hillslope erosion, BE is channel bank erosion, $BedE$ is channel bed erosion, and GE is gully erosion. Each component was parameterised stochastically from probability distributions derived from field surveys, laboratory sediment analysis, remote sensing datasets (NDVI, LiDAR), and published literature.

Hillslope erosion (HE) was estimated using the Revised Universal Soil Loss Equation (RUSLE) (Wischmeier & Smith, 1978) with parameters specific to Australian conditions derived by Yu and Rosewell (1996). RUSLE factors were parameterised from a combination of field-collected soil samples (particle size distribution, bulk density, organic content), slope and length factors derived from 1 m LiDAR terrain data, and cover factors estimated from Sentinel satellite NDVI datasets using the methods of van der Knijff et al. (1999) and Durigon et al. (2014), capturing both wet and dry season vegetation states. The rainfall erosivity factor (R) was calculated annually using the modified Fournier index approach of Renard and Freimund (1994), applied to a 1,000-year stochastic synthetic rainfall and hydrological dataset.

Bank erosion (BE) followed the stream power-based approach of Wilkinson et al. (2006), incorporating stochastic representations of bank height, proportion of bank vegetated, and the floodplain factor (accounting for bank erodibility/resistance due to margin confinement) of DeRose et al. (2002). Bed erosion (BedE) was parameterised from field observations and measurements of scour depth, channel width, and sediment bulk density (generalised from sediment samples across the catchment). Gully erosion (GE) was estimated from gully cross-sectional areas and lengths digitised from LiDAR and field measurements, using a characteristic gully age of 100 years following Wilkinson et al. (2006).

Sediment transport capacity (STC) at the pool reach was modelled using an extended form of Yang's (1973) stream power equation for bedload sediment transport (Prosser et al., 2001):

$$STC = K_1 \frac{12 * Q_m^{\beta} * S_{lr}^{\gamma}}{W_{lr}^{\beta-1}}$$

Where K_1 is a sediment transport coefficient dependent on particle size and hydraulic roughness, Q_m is monthly discharge, S_{lr} is channel slope of the reaches within the lower catchment (transfer and depositional zone which drive transport limitation), and W_{lr} is channel width within the lower catchment. STC was modelled stochastically, with exponents sampled from triangular distributions calibrated to the data of Prosser and Rustomji (2000). Effective sediment delivery to the pool was taken as the lesser of sediment supply and STC, reflecting supply and transport-limited conditions respectively.

Results were compared between baseline and modelled scenarios to quantify changes in median fine (silts and clays less than 60 μm) and coarse (sands and gravels larger than 60 μm) sediment delivery attributable to catchment contraction. Probability distributions (obtained via the Monte Carlo approach) of outcomes accommodated assessment of the full range of possible trajectories rather than single-point estimates.

Component 2: Event-based sediment delivery modelling

The event-based model disaggregates long-term sediment delivery into constituent flow events to identify which flow magnitudes drive sediment delivery trends and whether their relative contribution changes between scenarios. This is important because changes in catchment configuration may disproportionately affect certain aspects of sediment delivery (sediment supply and/or transport capacity) – for instance, by removing steep headwater areas that contributes coarse sediment primarily during large events.

The model was applied across six Annual Exceedance Probability (AEP) events (50%, 20%, 10%, 5%, 2%, and 1% AEP), corresponding to 24-hour rainfall depths. Bank, bed, gully, and transport capacity components were disaggregated from long-term values by assuming linear scaling with flow (for bed and bank erosion, and transport capacity) and rainfall (for gully erosion). Hillslope erosion was recalculated event-specifically using the RUSLE with a daily erosivity function developed for tropical Australian conditions (Yu, 1998):

$$R_j = 0.79\left(1 + 0.29\cos\left(\frac{2\pi}{365}j - \frac{\pi}{6}\right)\right)R_k^{1.49}$$

Where R_j is rainfall erosivity for day j of the year, and R_k is event rainfall depth. Event rainfall and discharge inputs were sourced from the same dataset as the long-term stochastic sediment delivery model. A stochastic Monte Carlo framework was applied again, this time using 10,000 iterations to characterise variability in event-based delivery outcomes due to increased calculation times.

Comparison of event-based delivery between baseline and developed scenarios resolved both the direction and event-frequency dependence of changes in fine and coarse sediment supply – information unattainable from long-term modelling alone.

Component 3: Event-based flushing assessment

The flushing assessment evaluates the capacity of flow events to mobilise and transport sediment within the pool reach, operating complementary to the delivery models. That is, this assessment quantifies the volume of sediment (from delivery or pre-existing stores) that can be removed and transported downstream.

Sediment mobility was assessed using the Hjulström Curve parameterised by Miedema (2013), which provides threshold velocities for the onset of scour (erosion of bed sediment) and continued transport across a wide range of grain sizes. The transport threshold (above which already-mobilised sediment is conveyed) was:

$$U_T = \frac{77d}{1 + 24d}$$

Where d is grain diameter (assumed as the b-axis). The scour threshold (above which stationary bed material is entrained) was:

$$U_S = 1.5\left(\frac{\nu}{d}\right)^{0.8} + 0.85\left(\frac{\nu}{d}\right)^{0.35} + 9.5\frac{Rgd}{1 + 2.25Rgd}$$

Where ν is kinematic viscosity, R is relative sediment density, g is gravitational acceleration, and d is grain diameter. Assessments were conducted for various grain sizes spanning fine silt (0.002 mm) to cobbles (200 mm) representative of material found within the catchment, using event velocity time series derived from hydraulic modelling of the pool reaches. The duration of time within each event for which flow velocity exceeded scour and transport thresholds was calculated for baseline and modelled scenarios, and changes in these durations were interpreted as changes in the pool's capacity to mobilise and export sediment of various fractions.

This component is particularly important because the reduction in catchment area under developed conditions not only alters sediment supply but also hydraulic energy in the pool reach. Understanding whether the reduction in flushing capacity is greater or lesser than the reduction in supply is fundamental to predicting net changes in pool sediment storage.

Synthesis: The sediment flux balance

Results from the three modelling components were synthesised through a conceptual sediment flux balance that resolves indicative changes to in-pool sediment storage (δS) as a function of changes in delivery, transport, and scour:

$$\delta S = \delta delivery - \frac{(\delta transport + \delta scour)}{2}$$

This model conceptualises the pool as a node within a sediment cascade (sensu Fryirs et al. 2007). Sediment entering the pool reach from upstream sediment delivery is either transported through the reach to downstream sections, deposited within the pool, or available for scour from existing pool stores during energetic flow events, as represented in Figure 2. The net change in pool sediment storage reflects the balance between these fluxes.

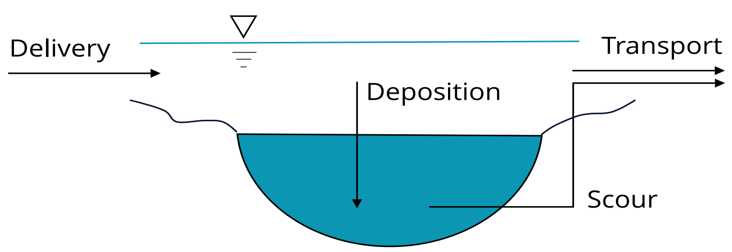

Figure 2 Conceptual model of sediment dynamics within a pool used to evaluate fluxes in sediment storage

The key diagnostic question addressed by the synthesis is whether reductions in sediment delivery are greater or lesser than reductions in flushing capacity (transport + scour). Where sediment delivery reductions outpace flushing reductions, the pool is expected to progressively lose sediment (net storage decrease); where flushing reductions exceed delivery reductions, sediment is expected to accumulate (net storage increase). This asymmetry is a direct consequence of the spatial pattern of catchment contraction – specifically, which parts of the catchment are removed by development and how those areas contribute differentially to sediment supply versus hydraulic energy.

Critically, this synthesis was applied separately to fine and coarse sediment fractions (albeit without considering the effects of fine sediment cohesion), recognising that these behave very differently within pool reaches. Fine sediment is more readily transported as suspended load and is disproportionately subject to capture by riparian vegetation; coarse sediment is transported as bedload and requires greater shear stress for entrainment and is more closely coupled to hillslope and channel erosion processes, typical of the sediment generating nature of upper catchments in the Pilbara. Changes in the fine-to-coarse ratio of pool sediment storage have direct implications for pool substrate composition and associated ecological conditions.

The model did not consider suspended load transport limits or hysteresis but rather assumed complete transport of fine sediments as suspended load. Likewise, partial mobility bedload transport was not considered due to the simplification of sediment to a single median particle size.

This multi-component synthesis provides a semi-quantitative trajectory of pool sediment system evolution under altered catchment boundary conditions – not a precise prediction of pool morphology, but a physically grounded basis for rating impact likelihood and severity, articulating the mechanisms of potential change, and identifying the dominant process controls.

Application: A mine extension in the Pilbara

Study context

The framework was applied to assess potential impacts of a proposed mine expansion on pool habitats in a waterway system in the Pilbara region of Western Australia. The project involved the expansion of an existing iron ore mine into a catchment containing several pools classified under the Australian National Aquatic Ecosystem (ANAE) framework (Aquatic Ecosystems Task Group, 2012).

The study area is characteristic of Pilbara headwater systems, featuring bedrock-confined and partly confined channels with steep upper catchments grading to broader, partially alluvial reaches in lower elevations. Catchments are underlain by the Corboy and Kangaroo Caves Formations, which comprise iron-rich shales, sandstones, banded iron formations, and chert. Soils are predominantly shallow, stony deposits of the Capricorn system, with high coarse fractions (typically >70%). The climate is semi-arid monsoonal: mean annual rainfall of approximately 360 mm is concentrated in January to March, with flow generation dominated by episodic high-intensity cyclonic and convective events and extended periods of no flow. This extreme hydrological variability is characteristic of Pilbara dryland rivers (Tooth, 2000; Tooth & Nanson, 2011).

The project footprint reduces catchment area reporting to two pools warranting quantitative sediment assessment. These pools span two water permanence classes defined by satellite imagery analysis: a permanently inundated pool (Pool A; baseline catchment area 294 ha, reducing to 124 ha under development, a 58% reduction); and a commonly wet pool (Pool B; 366 ha reducing to 316 ha, a 14% reduction).

Long-term sediment yield results

Under baseline conditions, Pool A received a median total sediment load of approximately 5,670 t/year (90% confidence interval: ±33 t/year), of which coarse material accounted for approximately 72% (4,080 t/year). Pool B received a similar median total delivery of approximately 5,410 t/year, with a coarse-fine split approaching equal volumes. In both cases, distributions were strongly positively skewed (mean substantially exceeding median), confirming that long-term sediment delivery is dominated by infrequent high-magnitude events – a general characteristic of dryland sediment systems (Laronne & Reid, 1993; Tooth, 2000).

Under developed conditions, Pool A exhibited a 55% reduction in total sediment delivery (to 2,545 t/year median), with equivalent reductions in fine and coarse fractions, reflecting the relatively uniform erodibility of the removed catchment area. Pool B displayed a moderate overall reduction (21%), with a larger fine fraction reduction (31%) as compared to coarse (13%), indicating that the areas removed from this catchment preferentially supplied fine material. This fractional asymmetry has important implications for substrate composition trajectories under development.

Event-based delivery results

Event-based modelling largely corroborated the long-term results while providing additional resolution on event-frequency dependence. For Pool A, fine and coarse sediment delivery decreased by a consistent 63% and 57% respectively across all AEPs (range of variation across AEP's: 3–4%), indicating that the removed catchment area was spatially uniform with respect to runoff-generating processes at all flow magnitudes. For Pool B, mean reductions of 36% in both fractions were observed but with higher variability across AEP's (range of variation across AEP's ~23%), suggesting that the contributing sub-catchments interact differently with different event magnitudes and highlighting the importance of undertaking an event-based assessment to supplement the long-term assessment.

Event-based flushing assessment results

The flushing assessment revealed important asymmetries in how hydraulic energy changed within pool reaches under developed conditions. For Pool A, mean reductions in fine sediment scour (44%) and transport (18%) across assessed AEPs (1% to 50%) were smaller than the corresponding reduction in fine delivery (63%), indicating that flushing capacity declined less than supply. For coarse material, transport capacity declined dramatically (70% mean), exceeding the delivery reduction, particularly for moderate-to-frequent events. This pattern implies that reduced coarse sediment delivery will not be fully compensated by reduced export – coarse sediment storage is expected to decrease slightly – while fine sediment storage will undergo a moderate decrease as reduced scour and transport still out-retain the reduced supply.

For Pool B, flushing reductions were comparably modest across both grain sizes (fine scour -11%; fine transport -4%; coarse scour -18%; coarse transport -12%). This pattern is similar to Pool A but of lower magnitude, consistent with the smaller degree of catchment contraction.

Impact assessment and synthesis

Synthesising across all three components through the sediment flux balance, the following trajectories were inferred for each pool:

- Pool A (Permanent): Large decreases in fine sediment delivery, combined with slight decreases in fine scour and transport, produced an expected moderate decrease in fine sediment storage. Coarse sediment storage was expected to experience only a slight decrease due to large reductions in coarse transport partially offsetting delivery reductions. The net expected effect was a gradual transition toward a relatively coarser substrate, with reductions in pool turbidity due to modest decreases in soft sediment substrate, and persistence of fine sediment in vegetated pool margins.

Table 1 Sediment assessment results for changes following mine development in Pool A

	Parameter	Scour	Transport	Delivery	Storage[1]
Fines					
	Event mean	-43.5%	-17.5%	-63.3%	-32.8%
	Long-term	-	-	-56.0%	-25.5%
Coarse					
	Event mean	-33.3%	-69.6%	-56.7%	-5.3%
	Long-term	-	-	-56.0%	-4.6%

[1] Calculated using indicative equation for δS. Values are indicative of likely direction of flux and approximate magnitude but are not estimates of real outcomes.

- Pool B (Commonly Wet): Moderate decreases in fine and coarse delivery with only slight decreases in flushing capacity produced an expected slight decrease in both fine and coarse sediment storage. The pool's bedrock confinement and exposed bedrock substrate with limited evidence of existing accumulation, however, were expected to limit the expression of sediment change (due to low existing storage and substrate strong resistance). Therefore, pool morphology was not expected to exhibit significant change.

Table 2 Sediment assessment results for changes following mine development in Pool B

	Parameter	Scour	Transport	Delivery	Storage[1]
Fines					
	Event mean	-10.7%	-4.2%	-35.8%	-28.4%
	Long-term			-31.0%	-23.6%
Coarse					
	Event mean	-18.2%	-12.1%	-35.9%	-20.8%
	Long-term			-13.0%	+2.2%

[1] Calculated using indicative equation for δS, values are indicative of likely direction of flux and approximate magnitude but are not estimates of real outcomes.

Conclusion and implications for stream management

This study suggests that the response of dryland pool sediment systems to catchment disturbance cannot be reliably characterised by any single metric. The three-component framework presented here – integrating stochastic long-term sediment yield modelling, event-based delivery disaggregation, and hydraulic flushing assessment – provides a level of diagnostic capability that is qualitatively superior to conventional single-model approaches and directly relevant to the decisions that environmental impact assessments must support.

Three contributions are particularly noteworthy. First, the stochastic Monte Carlo approach produces probabilistic sediment delivery distributions rather than point estimates, which is appropriate for the highly variable dryland environment and directly supports the characterisation of impact severity ranges which can be used to inform qualitative evaluations rather than binary outcomes. Second, the event-based disaggregation reveals temporal variability (how delivery changes under development across events of different magnitudes) that are invisible to long-term averages. Third, the flushing assessment resolves the supply-removal balance within the pool, providing the mechanistic basis for inferring net storage change rather than assuming that changes to delivery encompass impacts to pools.

The sediment flux balance synthesises these components into a tractable, semi-quantitative framework for articulating impact trajectories, recognising that the goal of impact assessment is not precise morphological prediction but defensible characterisation of likely direction, magnitude, and mechanism of change. This aligns with the broader call in the geomorphic literature for process-based assessments that resolve the physical mechanisms of channel response while respecting the complex and uncertain nature of fluvial systems, rather than defaulting to empirical relationships of uncertain applicability (Brierley & Fryirs, 2005; Fryirs & Brierley, 2013).

From a stream management perspective, the framework supports several practical outcomes. It identifies which pools are genuinely at material risk of sediment regime change (allowing management effort to be concentrated on high-risk sites), articulates the specific mechanisms of potential impact (guiding targeted monitoring design and management interventions), and provides a physically grounded basis for evaluating the effectiveness of proposed mitigation measures (e.g., sediment control infrastructure) in the future. Where catchment area reduction is planned or inevitable, the framework provides the process understanding needed to anticipate new geomorphic states (aggrading, degrading, fining, etc.) and manage toward geomorphic and ecologically acceptable trajectories.

The framework is transferable beyond the Pilbara context. Any dryland or semi-arid pool system subject to catchment configuration change, whether from mining, land use change, flow regulation, or climate-driven shifts in effective contributing area, presents an analogous process-assessment challenge. The components are individually established in literature and collectively novel in their integration. With appropriate parameterisation, this framework offers a replicable approach to a class of impact assessment problems that is likely to grow in frequency and consequence as human pressures on dryland water resources intensify.

Future work should seek to validate the framework predictions against monitoring data from impacted and comparable systems and refine the manner in which fine and coarse sediment loads are handled to better reflect their respective behaviour (e.g., regarding cohesiveness and different mechanisms of transport (bed load vs. suspended load). Future work should also consider whether the modelled reduction in sediment supply could generate sediment-starved flow conditions with increased erosive capacity leading to increased bank and bed scour within channels.

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