Quantifying sediment export from evolving mine landscapes: Hybrid modelling framework for adaptive catchment management

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Key points

- A hybrid modelling framework combining the process-based GeoWEPP model with a stochastic Monte Carlo sediment delivery model (SSDM) was applied across 173 sub catchments at a large open-cut coal mine in semi-arid central Queensland to quantify sediment export and identify erosion hotspots.
- Despite structural differences in model architecture, GeoWEPP and the SSDM showed broad spatial agreement in identifying high-risk catchments, supporting the use of dual-model approaches to increase confidence in sediment management decisions.
- The framework demonstrates a scalable and transferable approach for adaptive catchment management at mine sites subject to regulatory scrutiny, where robust quantification of sediment risk is required to inform mitigation design.

Abstract

Active extraction, progressive rehabilitation and changing land cover produce spatially variable erosion and sediment transport conditions that present significant challenges for mine catchment management. Where regulatory obligations require quantification of offsite sediment delivery, single-model approaches may lack the confidence or spatial resolution needed to prioritise intervention effectively.

This paper presents a hybrid modelling framework developed for a spatial erosion assessment at a large open-cut coal mine in semi-arid central Queensland. The framework couples GeoWEPP, a process-based continuous simulation model, with a Stochastic Sediment Delivery Model (SSDM), incorporating Revised Universal Soil Loss Equation (RUSLE)-based hillslope, gully, channel bed and bank erosion and sediment transport capacity, evaluated through 50,000 Monte Carlo iterations per catchment (X. Yang & Yu, 2015). The approach was applied across 173 hydrological sub catchments spanning the different sectors of the mine, using a 2.5 m resolution digital elevation model (DEM), site-specific soil erodibility, Normalised Difference Vegetation Index (NDVI)-derived cover factors, and other supporting data.

Results identified substantial spatial variability in sediment export across all sectors, with median catchment yields ranging from less than 1 t/ha/yr to over 230 t/ha/yr. Sediment export was concentrated in a small number of catchments characterised by steep, bare, non-engineered surfaces and limited downslope retention. Despite differences in modelled export magnitude, GeoWEPP and the SSDM showed strong spatial agreement in identifying high-risk catchments, increasing confidence in hotspot delineation.

The framework demonstrates how dual-model sediment assessments can directly inform rehabilitation prioritisation under regulatory and operational constraints.

Keywords

GeoWEPP, RUSLE, Stochastic sediment delivery modelling, Erosion hotspot delineation, Mine catchment hydrology, Sediment delivery ratio, Landscape rehabilitation, Adaptive catchment management

Introduction

Open-cut coal mining in Queensland generates some of the most erosion-prone landscapes in Australia (Erskine & Fletcher, 2013). Extraction progressively exposes large areas of stripped, reworked and re-graded material with high surface erodibility, steep constructed slopes and limited vegetation cover (Hancock et al., 2008). Mine landscapes are not static, they evolve continuously as mining advances, waste dumps expand, haul roads are constructed and rehabilitation is progressively applied. This temporal and spatial variability in surface conditions produces highly dynamic erosion and sediment transport behaviour that is difficult to characterise using conventional assessment approaches.

Offsite sediment export from mine catchments is a recognised environmental concern in Queensland, with potential for fine sediment to degrade downstream waterways and receiving environments of high ecological value (Bartley et al., 2007).Regulatory frameworks under the Environmental Protection Act 1994 (Qld) require mine operators to manage and minimise sediment discharge, and where environmental incidents occur, Environmental Evaluation notices may direct operators to characterise erosion source areas, quantify sediment delivery pathways and demonstrate that existing controls are adequate to protect downstream receiving environments.

Empirical models such as the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) have been widely used in Queensland mine settings to estimate hillslope erosion rates (Loch et al., 1998).While RUSLE-based approaches provide a practical screening tool, they do not represent spatial variability in erosion and deposition processes within a catchment, nor do they account for the full suite of sediment sources, including gully erosion, channel bed erosion and bank erosion that contribute to sediment loads entering the receiving environment. Process-based models such as the Water Erosion Prediction Project (WEPP) (Lane & Nearing, 1989) offer greater physical realism and spatial resolution and have been validated against measured erosion rates on rehabilitated mine batters in Western Australia (Howard & Loch, 2019)

Stochastic and probabilistic approaches offer a complementary means of characterising this uncertainty. Monte Carlo simulation frameworks have been applied to mine site erosion assessment in Australia (Evans et al., 2004). However, combination with a spatially explicit process-based model in a dual-model validation framework has not been reported for an active open-cut coal mine setting in Queensland.

This paper presents a hybrid modelling framework that couples GeoWEPP with an SSDM to quantify sediment export and identify erosion hotspots across 173 sub catchments spanning different sectors of the mine. The framework was developed, with the explicit purpose of providing a spatially explicit, quantitative basis for prioritising rehabilitation and mitigation under adaptive catchment management.

Methods

Study area

The study site is a large open-cut coal mine in semi-arid central Queensland, operating within the Bowen Basin. The mine comprises active pit areas, waste rock dumps, haul roads, sediment detention infrastructure and progressive rehabilitation at varying stages of vegetation establishment. Annual rainfall is characterised by high inter-annual variability and episodic high-intensity events, producing erosive conditions across exposed mine surfaces for much of the year.

Stage 1 and Stage 2 of this assessment applied RUSLE-based screening to identify catchments with potential sediment loss exceeding 10 t/ha/yr. Stage 3 involved detailed spatial erosion modelling across all catchments flagged in Stage 2, with 173 hydrological sub catchments modelled across the three sectors of the mine.

Overall modelling approach

Sediment delivery modelling was undertaken using two independent approaches applied concurrently: a process-based spatial model (GeoWEPP) and a stochastic Monte Carlo sediment delivery model (SSDM). The dual-model approach was adopted to increase confidence in hotspot identification, characterise uncertainty in predicted sediment export and provide a basis for cross-model validation. Catchments were classified as either engineered (haul roads and associated infrastructure) or non-engineered (spoil, stripped and natural surfaces) based on aerial imagery interpretation. Model outputs were compared using median sediment export at the sub catchment outlet, with spatial agreement in the relative ranking of catchments used as the primary criterion for hotspot classification.

GeoWEPP

GeoWEPP is a continuous, process-based model simulating rainfall infiltration, surface runoff, soil detachment, sediment transport and deposition via physically based equations (Lane & Nearing, 1989), including inter-rill and rill erosion processes and channel sediment routing.

A 2.5 m resolution digital elevation model (DEM) supplied by the client was used as the terrain input. Catchments were delineated using a 0.1 ha contributing area threshold and a 100 m minimum channel length. For one large catchment (approximately 475 ha), the DEM was resampled to 5 m resolution to enable model execution within acceptable run times; this was not considered to materially affect catchment boundary delineation or the primary mechanisms of sediment mobilisation.

Climate inputs were derived from a 30-year dataset extracted from the nearest Bureau of Meteorology station with an appropriate record, processed through the CLIGEN stochastic weather generator to produce 100 years of synthetic daily climate data. Soil inputs were developed from site-specific erodibility testing, with separate parameter sets assigned to engineered and non-engineered surface types. Hydraulic conductivity was varied, based on relationships established by site-specific infiltration testing. Land cover was assigned to each hillslope element using RUSLE C factors derived from NDVI imagery.

Stochastic Sediment Delivery Model

The SSDM was developed to validate GeoWEPP outputs and characterise variability in sediment export outcomes using a Monte Carlo simulation framework. A total of 50,000 iterations were completed per catchment, with input parameters sampled stochastically from defined probability distributions at each iteration. Sediment export was recorded for each iteration and summarised using the median, given the strong positive skew of sediment export distributions.

Sediment supply within the SSDM was estimated from four component processes:

1. Hillslope erosion was calculated using the RUSLE (Revised Universal Soil Loss Equation)

   $$HE = R * K * LS * C * P * A_c * SDR$$

   Where R is rainfall erosivity calculated using the methods set out by (Yu & Rosewell, 1996). K is soil erodibility; LS is the length-slope factor calculated using the method described by (Renard et al., 1997); C is the cover management factor calculated using the method proposed by (Durigon et al., 2014); and P is the support practice factor. Additionally, A_c is catchment area and SDR is the sediment delivery ratio.

2. Gully erosion was estimated as a function of gully cross-sectional area, length and age using the approach described by (Wilkinson et al., 2006). Gully length was determined from hydrological analysis of the DEM using a 1,000 m^2 contributing area threshold.

3. Channel bed erosion was estimated based on an assumed bed scour rate applied to channel length and width, with channel geometry derived stochastically using the regime equations of (Leopold & Maddock, 1953).

4. Channel bank erosion was calculated using the stream power approach, with discharge estimated from the rational method and bank height derived from Manning's equation (Wilkinson et al., 2006).

For catchments containing defined channel networks, sediment transport capacity was calculated using a modified form of (C. T. Yang, 1973) sediment transport equation as implemented by (Wilkinson et al., 2006) with sediment export taken as the minimum of total sediment yield and transport capacity.

Results and discussion

Sediment export modelling across the 173 hydrological sub-catchments identified substantial spatial variability in erosion and sediment delivery. Results were strongly positively skewed, with a small proportion of sub-catchments contributing disproportionately to total offsite sediment export. GeoWEPP median yields ranged from 0.1 to 144.5 t/ha/yr across the full assessment area, while SSDM medians ranged from 0.2 to 236.0 t/ha/yr. The majority of sub-catchments produced relatively low median yields under both models, while a subset exceeded the 50 t/ha/yr management threshold and were classified as sediment export hotspots requiring priority intervention.

Table 1 Modelled median sediment export for sub-catchments exceeding the 50 t/ha/yr management threshold, with inter-model agreement classification

Sub-catchment	GeoWEPP (t/ha/yr)	SSDM (t/ha/yr)	Inter-model agreement
CS05.02	144.5	235.5	Strong (hotspot)
CO05.01	128.1	236.0	Strong (hotspot)
CS11	131.4	107.3	Strong (hotspot)
H28A	79.8	–	GeoWEPP only
P15_01	59.5	46.2	Strong (hotspot)
S04_01	47.3	50.8	Strong (hotspot)
P27	117.3	54.8	Divergent – review
S04_02	84.4	17.3	Divergent – review
P15_02	70.0	23.9	Divergent – review

The SSDM consistently produced higher median sediment export estimates than GeoWEPP across most sub-catchments (Figure 1). Despite these magnitude differences, both models showed broad spatial agreement in identifying sub-catchments with comparatively higher or lower sediment delivery potential, which formed the primary basis for hotspot classification.

Where inter-model agreement was strong, confidence in hotspot classification was substantially increased. The highest-yielding sub-catchments (Table 1) returned elevated estimates under both models and are predominantly characterised by steep, bare or poorly vegetated surfaces with concentrated flow paths and limited downslope sediment retention.

A number of sub-catchments showed marked inter-model divergence (Table 1), with GeoWEPP estimates substantially exceeding SSDM outputs, likely reflecting differences in how each model treats sediment transport limitation and impoundment behaviour. These sub-catchments remain candidates for further field investigation prior to committing to mitigation design.

Engineered haul road and infrastructure catchments consistently produced low sediment yields under both models, generally below 5 t/ha/yr, confirming the relative erosion resistance of coarser compacted surfaces and the effectiveness of engineered drainage controls where these are in place.

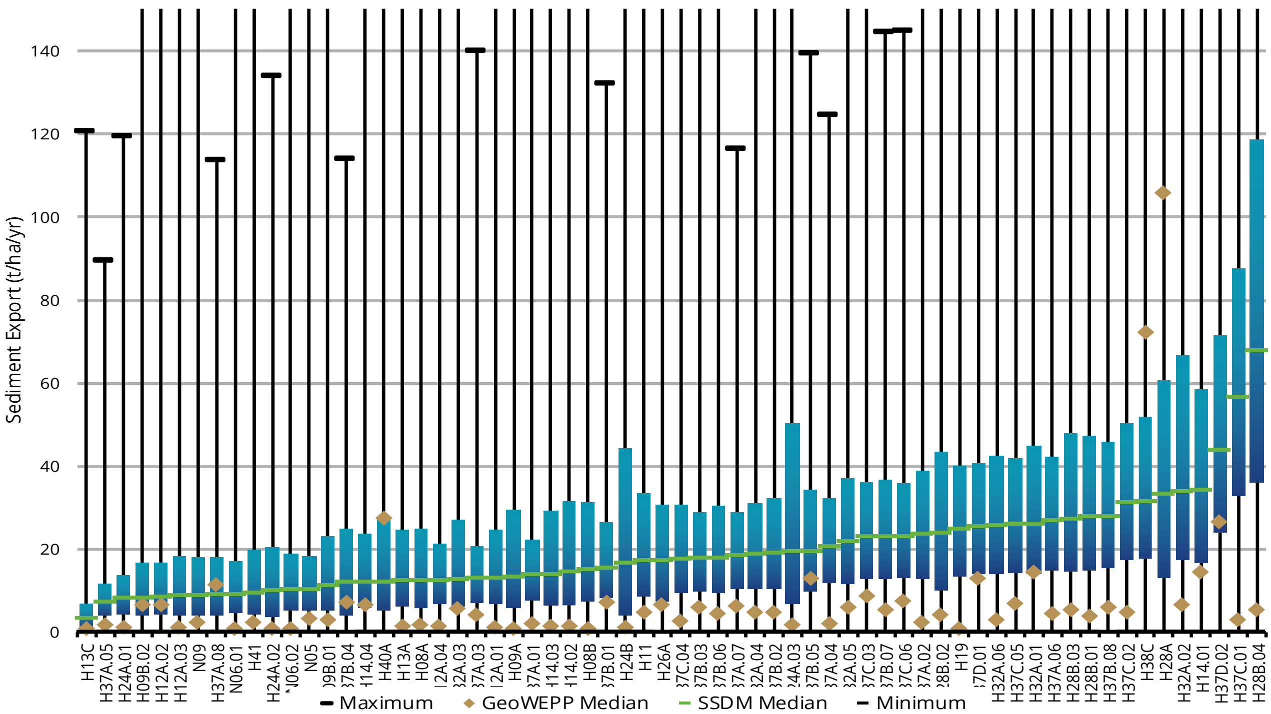

Figure 1 Comparison of GeoWEPP and SSDM median sediment export estimates by sub-catchment, H and N series sub-catchments

Model performance and confidence

The dual-model approach provided a more robust basis for hotspot classification than either model could offer independently. Where the two models diverged markedly, the divergence was driven primarily by gully erosion components absent from the deterministic model, and these sub-catchments warrant additional field investigation or model refinement prior to mitigation design.

The consistent tendency of the SSDM to produce higher median sediment export estimates than GeoWEPP across most sub catchments reflects fundamental structural differences between the approaches. GeoWEPP simulates a fixed-length 100-year simulation with a single CLIGEN-generated climate realisation period and does not explicitly account for long term variability in gully, bed or bank erosion processes, whereas the SSDM integrates all four sediment source components and represents long-term variability through stochastic iteration. The SSDM also does not simulate impoundment behaviour, which likely contributes to an overestimation of sediment delivery in sub catchments where detention infrastructure is present. Neither model was calibrated against measured sediment loads due to data limitations and results should therefore be interpreted in a relative rather than absolute sense. Notwithstanding these limitations, the spatial consistency between models in identifying priority sub catchments provides a defensible and transparent basis for rehabilitation prioritisation.

The modelled outputs are therefore decision-support tools rather than definitive quantifications of sediment yield. Their value lies in the relative ranking of sub-catchments and the spatial consistency of results across two independent frameworks, which together provide a rational and auditable basis for prioritising field investigation and rehabilitation effort.

Mine landscape evolution and sediment risk

Active extraction exposes new areas of highly erodible material, progressive rehabilitation alters surface cover and hydraulic conductivity, and constructed landforms create concentrated flow paths that persist long after initial earthworks are completed. The dominance of steep, bare, non-engineered surfaces among the highest-yielding sub-catchments aligns with established understanding of erosion dynamics on post-mining landscapes in central Queensland, where spoil material erodibility and slope geometry are the primary controls on sediment generation.

Dynamic landscape conditions and model limitations

The modelling undertaken in this assessment is based on static inputs representing conditions at the time of assessment, including a fixed DEM, a single soil erodibility parameterisation and vegetation cover derived from NDVI imagery captured at a specific point in time. These inputs will progressively diverge from actual catchment conditions as extraction advances, spoil is emplaced and rehabilitation alters surface cover and terrain geometry. Periodic reassessment with updated inputs is recommended as significant landscape changes occur throughout the mine life cycle.

Management Implications

By identifying which catchments contribute disproportionately to offsite sediment delivery, the framework allows rehabilitation and mitigation resources to be targeted where they will achieve the greatest environmental benefit. This provides the quantitative evidence base needed to justify intervention sequencing and demonstrate progressive improvement in catchment condition, particularly as mines approach closure.

As rehabilitation progresses, model inputs, particularly the RUSLE C factor derived from NDVI imagery, can be updated and re-run to assess whether sediment export risk has been sufficiently reduced. This specific dual-model combination has not previously been reported for an active open-cut coal mine in Queensland, representing a methodological contribution to the mine rehabilitation literature.

Conclusions

Across 173 sub catchments at a large open-cut coal mine in semi-arid central Queensland, sediment export was highly concentrated in a small number of sub catchments associated with steep, bare, non-engineered surfaces, with peak median export reaching 236 t/ha/yr under the SSDM. Engineered surfaces consistently produced low yields under both models, and both models agreed spatially on the identity of priority sub-catchments, providing a transparent basis for mitigation design.

The hybrid approach combines the spatial precision of a process-based model with the uncertainty characterisation of a stochastic framework, providing a robust and adaptive tool for directing rehabilitation effort in dynamic mine landscapes.

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