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Review

An Approach to Assess Land Stability and Erosion on Mined Landforms

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Abstract: Where mining activities cause disturbance in catchments, streams are often impacted by heavy loads of fine eroded material. Since geomorphological processes are very slow, it is expected that during rehabilitation, typically hundreds of years are required for a mine landform to return to stability. A sensitive approach to analyzing post-mining landform stability in tropical regions is to assess the quantity of fine suspended sediments (FSS = silt + clay (0.45 μm < diameter < 63 μm)) leaving the catchment where the mine resides and entering the receiving streams in response to storm events. Continuous stream discharge and FSS quantities upstream and downstream of the catchment where the mine resides were modeled using the HEC-HMS (Hydrologic Engineering Centre–Hydrologic Modeling System). Once calibrated, the model was run for a thousand years to predict continuous stream discharge and FSS quantities for various predicted rainfall scenarios. Short-term erosion and deposition across the mine catchment were also evaluated using a calibrated landform evolution model, CAESAR-Lisflood. This paper reviews watershed soil erosion measurements and modeling research leading to the abovementioned approach. This approach assesses mine landform erosion and stability in terms of fine suspended sediments. It can be used to determine mine landform erosion dynamics, predict the achievement of landform stability equilibrium, and as a post-mining rehabilitation assessment tool.

Keywords: sediment movement; watershed; erosion processes; modeling; mined landform

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1. Introduction

1.1. Geomorphology and Land Reclamation

Human actions directly affect geomorphology and guide landscape change. Processes that change landscapes over time, in turn, dictate the ecosystems and human activities that can exist in a given place [1]. The percentage of the Earth's land surface altered by human earth-moving activities has increased significantly in recent decades. Over 50% of the planet's ice-free land area has been directly modified by human action, and land use change has affected 32% of the global land area over the past six decades (1960–2019) [2]. Many of these activities have indirect effects that extend far beyond the directly affected areas [3], and in many cases, the consequences may extend long into the future.

Environmental impacts of the changed landscapes can be significant, and impacts must be understood, managed, and reduced to the greatest extent possible. These new landforms often lead to accelerated erosion and landscape evolution [4]. Resulting erosion products are deposited as colluvium on hillslopes, alluvium on floodplains, and as lacustrine deposits, and streams and rivers carry away the rest. Runoff from these areas typically contains high sediment loads after major earth movement activities have occurred. Changes in flow regimes due to geomorphic changes can result in flooding, debris flows, and slope failure, with the potential, at the most serious level, to cause loss of human life. Impacts on infrastructure and economic losses may occur. Thus, landscapes modified by earth movement activity are becoming a key issue, and therefore, management of the environmental effects of the new landform is of paramount importance.

1.2. Mining and Soil Erosion

Minescapes are landscapes generated by mining activity. After mining activity, instability of landforms and erosion of large minesites has the potential to have severe long-term environmental impacts. Most of the research and literature on minescape stability has primarily concentrated on geomorphological assessments of catchments impacted by mining activities. Hydro-geomorphologic studies (together with environmental geochemistry) have a leading role in understanding the cause of problems on the subsequent rehabilitated mined areas [5]. A diverse range of engineering strategies are employed to ensure stability and erosion control, but there is concern about the prolonged effectiveness of many engineering strategies employed in the rehabilitation of mined lands. The successful restoration of mined land is acknowledged as a crucial element of sustainability in the mining industry [6].

Rehabilitation of disturbed sites involves restoring the land to an acceptable condition and intended end use, a process that usually occurs in multiple stages and may take many years to complete [7]. What is an acceptable state depends on the criteria and values agreed upon by the company and government. Various methods to assess the success of mined land rehabilitation have evolved over time. The stability of the landform surface and its capacity to sustain suitable vegetation are fundamental requirements for rehabilitation [8].

An extensive assessment of mine site areas through satellite imagery revealed 24,605 mine areas from 117 countries that occupy a total area of 31,396 km^2 [9]. In Australia, it is estimated that inactive mines constitute around 89% of the total mines in Australia and only 4% of these inactive mines have been noted as rehabilitated. Mine site rehabilitation and mine abandonment are rising issues for Australian communities, governments, and taxpayers [10]. Historically, in Australia, to assess mining rehabilitation success, generally, prescriptive erosion rates were applied with no analysis of catchment morphology, soil types, or hydrology. As recently as 2016, there were no firm erosion rates set as rehabilitation guidelines [11]. Rates ranging from 2 t ha^{-1}y^{-1} to 12.6 t ha^{-1}y^{-1} were discussed such that the erosion rates did not result in rill or gully erosion, reduced stream water quality, or reduced soil productivity. The consequences of mining and its effects on associated processes can disturb land and water resources well beyond the area directly affected by mining. Thus, it is essential to evaluate the successful rehabilitation of above-grade landforms at the catchment scale with respect to erosion, catchment hydrology, and landform stability. This paper reviews an approach to assess post-mining landform stability and erosion equilibrium by simulating pulses of fine suspended sediments in the receiving waters of the catchment where the mine resides. It discusses the models used in the approach over others and analyzes the journal papers leading to the testing of the approach.

2. Erosion Modeling

2.1. Soil Erosion Models

Recently, there has been growing interest in software that utilizes fluvial geomorphic processes for assessing the design of landforms. Evaluating the success of mine site rehabilitation necessitates an understanding of how a landscape might evolve over time. Since geomorphological processes occur gradually, assessing the erosion and stability of rehabilitated landforms across many years requires modeling tools. Numerical Landscape Evolution Models (LEMs) are useful for examining the geomorphic behavior of landscapes, as they incorporate factors such as soil formation, climate, geology, and vegetation growth. These models can operate over time scales ranging from years to millennia and across spatial scales from sub-hectare to entire regions [12,13].

Landform stability is an important component of the landform design process and is mainly related to its erosion potential [8]. Models for predicting surface stability can generally be divided into two main categories, which are soil loss prediction or soil erosion models, which focus primarily on estimating erosion, and topographic evolution models (based on modeling erosion and accumulation of material across a landform over time) [14]. Soil loss prediction models have traditionally been designed for agricultural purposes. Some of the key soil loss prediction models that can be adapted for use in mining are RULSE, CREAMS, and WEPP [15].

The Revised Universal Soil Loss Equation (RUSLE) [16] is an empirical model for soil erosion that relies on statistical analysis of erosion data gathered from field plots. The RUSLE is designed for site-specific applications, allowing for the input of variables unique to a particular location. It estimates long-term average soil losses from fields under certain cropping and management practices, but it is not capable of modeling deposition. RUSLE remains the most commonly used model to predict surface erosion [17], and it was developed from the basic Universal Soil Loss Equation USLE model [18] after correcting some inaccuracies. There is a modified version of USLE called MUSLE [19] which was proposed before RUSLE and is still being used [20].

The Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model, developed by the United States Department of Agriculture, employs a process-based approach to predict erosion and sediment yield at a field scale [21]. This model includes components for hydrology and chemistry within a catchment area [22]. It uses a continuity equation to model sediment load, which changes downslope based on lateral sediment inflow and the detachment or deposition of sediment by flow. CREAMS considers rainfall, runoff, soil properties, and management practices. It calculates erosion on bare soils and applies empirical factors from the RUSLE to assess soil conservation efforts [23]. The model requires the determination of soil properties such as grain roughness and erodibility, and it can also simulate deposition.

The Water Erosion Prediction Project (WEPP) [24] is a processed-based model that predicts sediment transport and deposition across landscapes. WEPP differentiates hillslope erosion into two primary types: inter-rill and rill erosion. Inter-rill erosion involves soil particle detachment by raindrop impact and lateral movement into rill flow areas, whereas rill erosion refers to sediment detachment and transport by concentrated shallow flow channels [25].

2.2. Landform Evolution Models

Topographic Evolution Models (TEMs), also known as Landscape Evolution Models (LEMs), are process-response models that simulate material erosion and deposition over time across a landform. These models offer insights into the long-term geomorphological changes of a landscape affected by erosion and deposition processes [14]. They can also help predict the formation of drainage issues and gullies. Early models [26] focused on identifying aggradation areas, where material accumulated, and net erosion areas, where material removal was greater than accumulation. With advances in computing technology, these concepts are now applied to nodes on a Digital Terrain Map (DTM), allowing for 3D graphical simulations in newer models.

SIBERIA is an advanced 3D TEM that simulates both runoff and erosion to predict the long-term evolution of channels and hillslopes within a catchment area. It controls the gully formation locations and rates using a channel initiation function, affected by runoff and soil erodibility [27]. SIBERIA calculates two primary variables: elevation, which shapes slope geometries, and an indicator function that identifies potential channel locations. The model simulates the drainage system's development of a catchment by incorporating three sediment transport processes: tectonic uplift, fluvial processes, and mass movement. Channel growth is regulated by an activation threshold; a surface may lack gullies, but channels form once this threshold, determined by discharge and slope gradient, is surpassed. Although SIBERIA models both transport-limited and detachment-limited sediment transport, it is primarily used in transport-limited environments.

TEMs and LEMs need to include the movement of water across the landscape, as volumes and rates of water flow affect surface stability. A drainage basin simulation model [28,29] integrates the effects of mass-wasting, rain-splash, and fluvial erosion processes. GOLEM developed by Tucker [30] is a model that can simulate both detachment-limited and transport-limited sediment transport, predicting the specific areas of the landscape where each of these processes occurs.

The HEC-HMS (Hydrologic Engineering Center–Hydrologic Modeling System) [31] is a hydrologic modeling program that allows for the establishment of rainfall–runoff relationships, based on watershed characteristics. It simulates the complete hydrological processes of dendritic watershed systems, including many traditional hydrologic analysis procedures such as event infiltration, unit hydrographs, and hydrologic routing as well as sediment movement. It also includes procedures necessary for continuous simulation including evapotranspiration, snowmelt, and soil moisture accounting [32].

Lisflood is a GIS-based hydrological rainfall–runoff-routing model that simulates the hydrological processes within a catchment [33]. Unlike Lisflood-FP, Lisflood operates at a grid scale [34], modeling surface and subsurface processes by allowing water transport in both horizontal and vertical directions through the landscape and soil. It also accounts for lakes, reservoirs, and groundwater storage.

A component of TEM and LEM is the modeling of flood inundation. Flood inundation modeling today is performed mainly with the help of Lisflood-FP [34] or the HEC-RAS (5.0.3) (Hydrologic Engineering Center-River Analysis System) [35] which is a two-dimensional steady-flow hydraulic model used for channel flow analysis and floodplain determination. Numerous studies have utilized one-dimensional and two-dimensional (1D and 2D) numerical models to delineate floodplains. LISFLOOD-FP is a raster-based 2D model that applies an inertial formulation of the shallow-water equations, while the HEC-RAS is a versatile tool used by hydraulic engineers for a wide range of applications with varying levels of schematization complexity [36].

CAESAR-Lisflood [37] simulates landscape evolution by routing water over a grid of cells and adjusting the elevation of each cell based on erosion and deposition rates calculated from fluvial and slope processes. It integrates a hydrologic model (TOPMODEL) [38] and a hydraulic model (Lisflood-FP) [34] to predict landscape changes over time. A notable feature of CAESAR-Lisflood is its ability to incorporate variable time interval rainfall data that are specific to the study area, allowing for more tailored simulations.

3. Current Approaches and Gaps in Assessing the Erosion of Mined Areas

Most studies of mining landform evolution are site-specific and seldom adaptable to other sites. A major portion of studies focus on mine site risk assessment and mitigation rather than on an approach to track mine site rehabilitation success. Mine site rehabilitation assessments are either site-specific or general approaches that consider vast numbers of interrelated ecological or landscape parameters that are complex to assess over extended periods of time.

Most studies do not investigate the long-term landform changes after initial rehabilitation and closure. However, geomorphological processes are very slow, and the final rehabilitated landform can take centuries to form. Therefore, looking into the long-term effects of rehabilitation is a necessity. This also emphasizes the need for incorporating climate change impacts on mine rehabilitation and final landform formation.

Earlier studies did not focus on off-site impacts of mining which is another critical issue for successful mine rehabilitation. Potential environmental problems are not limited to the area directly affected by mining. Historically, some mining companies have had a poor record with respect to mine closure. This has resulted in a lot of community and regulatory pressure to improve rehabilitation and to include stakeholders in the rehabilitation process. For example, at the Rum Jungle uranium mine south of Darwin, Australia, mineral processing of uranium, nickel, copper, and lead stopped in 1971 but as of 2024, it is yet to be successfully rehabilitated. The mine site is located in the catchment of the East branch of the Finniss River. Poor rehabilitation design has resulted in polluted groundwater and then, together with poor performance of engineered soil covers, has resulted in acid drainage impacts on the Finnis River [39]. Acid rock drainage and contaminant loads to the Finnis River have had substantial impacts on the macroinvertebrate community, riparian vegetation, and fishes of the Finnis River system [40,41]. Water in the diverted channel of the Finniss River is sometimes discolored orange and brown due to contamination [42], which restricts public access, including for the First Nations Traditional Owners of the land. Rum Jungle was not handed over to Traditional Owners as part of the successful Finniss River land claim in case they became liable for the environmental problems [42]. Thus, serious consequences and environmental deterioration are faced by areas where sediments and contaminants from mine sites pollute downstream waterways.

The quality of the mine drainage water depends on a series of geological, hydrogeological, and mining factors, which are different from one mine to another. There are many examples from the USA and elsewhere to illustrate problems with substantial volumes of water from mining areas containing dissolved heavy minerals and carrying suspended particles downstream from the mined area. There have been instances of suspended sediment-related mining effects in Alto Tajo Natural Park, Spain [43]. Out of the downstream off-site impacts of mining activity, the water quality impact due to the sediment discharged from mines to the fluvial system can be one of the most deteriorating [44]. Increases in sediments affect the fluvial network in terms of infrastructure, such as reducing the water capacity of reservoirs [45], and they have detrimental ecological impacts on fish populations and their ecosystems [46]. Thus, monitoring suspended sediment in downstream waterways from mine catchments and alleviating its impacts is an indispensable step in offsite impact assessment.

Thus, a methodology to assess mine rehabilitation assessment that considers the offsite and long-term impacts of mining along with the incorporation of climate change impacts is essential. The methodology should be easily replicated in other similar landscapes to assess rehabilitation and the assessed parameter that indicates landform stability should be easily measurable to aid the provision of long-term and continuous data.

4. Development of an Alternate Approach

Landform design concepts are methods to assess various parameters of mine landform stability—especially erosion in and from the catchment where the mine resides. Mine rehabilitation is the process of bringing the parameters to match the agreed or acceptable values. To be considered successfully rehabilitated, the erosion properties of an above-grade landform need to be in equilibrium with the surrounding catchment. Howard [47–49] introduced an approach to the equilibrium concept in geomorphology. Equilibrium, as observed by him, refers to a type of temporal relationship between one or more external variables, or inputs, and a single internal variable, or output.

The Rate Law developed by Graf (1977) describes how a landform responds to disturbances that disrupt its equilibrium. According to the Rate Law [50] (Figure 1), an undisturbed geomorphic system (A) reacts to disruption in such a way that the system parameter Y (some dimensional or spatial characteristic of the system such as length or width) transitions to a steady state B after disruption where new conditions are internalized by the system. This is followed by a relaxation period C during which the system adjusts to new conditions. A new steady state is established in the next phase during D, resulting in altered dimensional characteristics. When considering the response of a minescape to mine rehabilitation, the goal is generally for steady state D to be restored to state A or something similar.

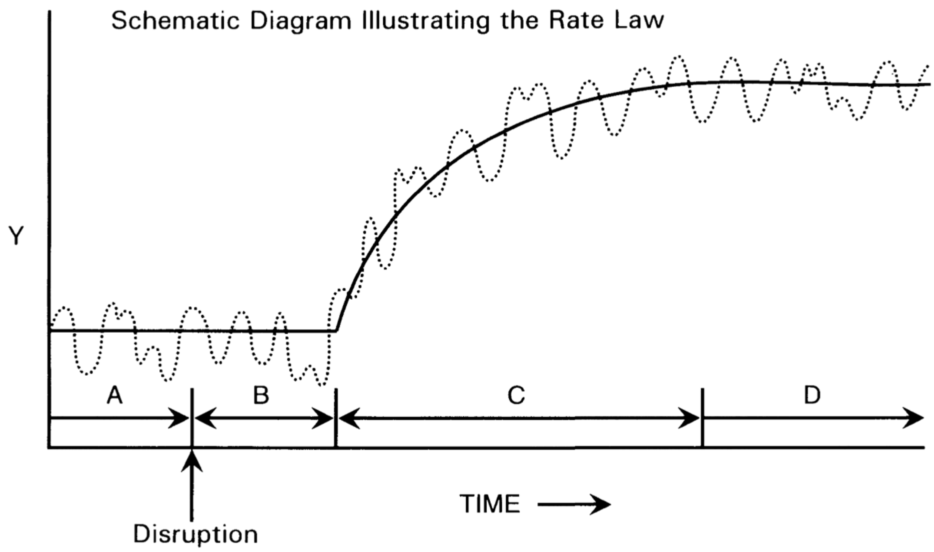

Figure 1. Representation of the Rate Law [50].

This temporal relationship has the following four characteristics [50]:

1. Changes in the inputs must result in measurable changes in outputs, either immediately or after a certain period. This criterion excludes cases where inputs have no impact on the output.
2. The output value at a given time should be related to the input value(s) at the same time by a single, time-invariant functional relationship, within an acceptable degree of accuracy.
3. The functional relationship must be testable in a repeatable manner, whether through experimental or observational methods.
4. An equilibrium relationship may only apply within specific ranges of input values and/or specific rates of change of input values.

Equilibria may be stable or unstable and may be simple (such as point attractors) or more complicated (such as cyclic attractors). Systems may have more than one equilibrium state rather than a single state toward which the unperturbed system will tend. Some outputs may not be measurable in the stipulated amount of time required for mine rehabilitation assessment since some geomorphological changes are very slow. Equilibria are scale dependent and determining them is constrained by the researcher's ability to handle a restricted number of variables simultaneously. Physically constraining the system (i.e., identifying the boundary of the landform under supervision) is essential in geomorphology [51].

The equilibrium concept in mine rehabilitation requires the landform stability parameters to return back to their pre-mining levels once the mine site is rehabilitated. An equilibrium approach to assess mine site rehabilitation was developed by Nair and Bellairs [52] for the Ranger mine, Northern Territory, Australia. It is expected to determine the time until the mine site is fully rehabilitated and the dynamics of a mine site returning back to stability after a disturbance. A suitable parameter to analyze is fine suspended sediment in downstream waterways of the mine catchment since it is an important parameter in mine site rehabilitation and offsite impact assessment. The aim of the approach was to determine how to assess if and when a rehabilitated mine landform has achieved erosion equilibrium with the surrounding catchment by using fine suspended sediment in stream water.

Fine suspended sediment quantity in the receiving waters of the mine landform as an indicator of landform stability was assessed by Nair and Evans [53]. Previous studies have used suspended sediment concentrations for monitoring disturbance by comparing values upstream and downstream of mine sites and with elevated trigger values to assess water quality deterioration [43]. Moliere and Evans [54] then developed the event FSS–discharge regression relationship following a rainfall event along with the BACI (Before and After Control Impact) approach to identify catchment disturbance. In Nair and Evans' study [53], the FSS–discharge relationship for rainfall events is used as a measure of erosional stability to identify the response to a known disturbance in the catchment (construction and revegetation of a trial waste rock landform). It evaluates rehabilitated mine landform stability based on FSS quantities in streams leaving the catchment where the mine resides. It assesses the variation in the fine suspended sediment discharge relationship upstream and downstream of a catchment. Turbidity is a surrogate measure of FSS that is easier to measure [55]. Since geomorphological processes are very slow, stability assessments must be performed for longer periods of time. The discharge and turbidity at the catchment outlet are easily quantifiable parameters that can be measured continuously, and thus, the data could be easily used for longer-term modeling and future simulations. Thus, it is much easier to collect continuous data using this method than slope stability, gully erosion, and incision depth evaluations, which were used as land rehabilitation assessment tools in previous studies.

Parameterization of hydrology and LEM models to enable longer-term simulations using FSS relationships to assess mining rehabilitation dynamics has been carried out. Nair and Evans [32] describe the parameterization of the hydrology model (HEC-HMS: https://www.hec.usace.army.mil/software/hec-hms/downloads.aspx (accessed on 10 January 2023)), and Nair and Evans [56] assess the parameterization of the landform evolution model (CAESAR-Lisflood: https://sourceforge.net/projects/caesar-lisflood/ (accessed on 24 February 2022)) for catchment modeling of the Ranger mine catchment. The HEC-HMS is an open-access hydrology model and CAESAR-Lisflood is an open-access landform evolution model. This avails calibration and validation of continuous fine suspended sediment quantity and discharge for the catchment model that can provide long-term future simulations. Subsequently, Nair and Bellairs [57] looked at the temporal variation in fine suspended sediment discharge from the catchment for 1000 years into the future using the calibrated models. This study uses hydrology model simulations to determine fine variations in fine suspended sediment quantity for a discharge to comment on landform equilibrium across hundreds of years into the future and a landform evolution model (CAESAR-Lisflood) to assess the erosion and deposition characteristics of the catchment. CAESAR-Lisflood takes a long time to run the full Gulungul catchment for extended periods of time. Therefore, the HEC-HMS was investigated to simulate sediment loss from the catchment that can be used as input to CAESAR-Lisflood, thus reducing the size of the DEM used in CAESAR-Lisflood and the time to iteratively design the final landform based on simulating erosion and sediment transport in receiving streams. The coupling of the models performed in this study reduces the runtime whilst not compromising the accuracy of model simulations.

The FSS relationship was used to evaluate the erosion equilibrium dynamics of a rehabilitated landform reaching equilibrium under different rainfall scenarios on account of climate change [57]. While that study focuses on landform equilibrium, the stream fine suspended sediment movement is an important factor as it is a major contributor to contaminant transport. The methodology can be easily interpreted graphically and understood by the stakeholders involved in or affected by the rehabilitation process. Table 1 details the steps leading to the approach discussed above.

Table 1. Steps to assess mine landform stability with stream-suspended mud [52].

Step 1	Determining the FSS-Q relationship at Gulungul upstream (GCUS) and Gulungul downstream (GCDS) with available data [53]
Step 2	Calibrating and validating the HEC-HMS for Gulungul upstream and downstream for discharge and FSS [32]
Step 3	Calibrating and validating CAESAR-Lisflood for Gulungul downstream for discharge and FSS [56]
Step 4	Running the calibrated HEC-HMS model at GCUS and GCDS for long-term continuous discharge and FSS data (from Step 2)
Step 5	Analyzing the FSS-Q relationship of simulated future events at GCUS and GCDS to determine the temporal variation (from Steps 1 and 4)
Step 6	Analyzing events for FSS spikes to determine erosion equilibrium and long-term landform stability (from Step 5) [57]

5. Outcomes and Achievements in the Face of Gaps

The approach was able to simulate the long-term erosion equilibrium of a rehabilitated landform [52], evaluate stream-suspended FSS as an indicator of landform stability [53], simulate long-term mine catchment evolution using Lisflood [56], and model an upstream catchment in the HEC-HMS [32] to simulate continuous discharge and FSS data for future years. The calibrated models were able to be used to run long-term simulations and evaluate the erosion equilibrium of the mine catchment [57] for centuries after rehabilitation in average, drier, and wetter climate scenarios.

Fine Suspended Sediment (FSS) spikes above the background relationship, in the creeks with catchments where the mine resides, can act as an indicator of catchment disturbance. The return to equilibrium of a landform following a catchment disturbance like mining can be determined by measuring the FSS load spikes and relating them to the expected relationship between event discharge (Q) and event FSS loads in the receiving streams following a rainfall event. This method is sensitive and can serve as a tool for evaluating mine landform rehabilitation. Field verification is essential to determine if the source of the disturbance is related to mining activities. This approach to assessing post-mining landform stability requires continuous monitoring of turbidity (which is taken as a surrogate measure of FSS) and discharge following rainfall events.

A major challenge to this methodology being used as a rehabilitation assessment tool, which needed to be resolved, was that the FSS-Q relationship following a rainfall event is subject to temporal variation. Since geomorphological processes are very slow, equilibrium changes in the mine catchment take centuries to occur. The baseline FSS-Q relationship determined from past rainfall events was valid for that time period. Assessment of FSS spikes for future events was performed in Nair and Bellairs' study [57] by simulating the catchment model for stream discharge and sediments in a hydrology model (HEC-HMS). The background relationship did not apply to simulated rainfall events that spanned centuries. The FSS-Q relationship determined from past events when applied for future simulated events gave higher FSS loads than the expected FSS values derived by modeling. This may be because the denudation rate of a landform decreased over the time period and thus the sediment erosion for a specific discharge also reduced along with it. Moreover, the temporal and spatial variability in the suspended sediment concentration in rivers are influenced by interactions between climate and catchment characteristics [58]. Thus, the FSS-Q baseline relationship must be updated for a time period to determine FSS spikes and thus the catchment disturbance.

The application of the approach to assess geomorphological changes in a rehabilitated mine landform for different rainfall scenarios was successful and the FSS loads returned to erosion equilibrium for the mine catchment after around 600 years [57]. It remained at erosion equilibrium for the rest of the 1000-year time period for which the average rainfall scenario was run. For the wetter rainfall scenario, it takes around 700 years until the

FSS event loads return to background equilibrium levels for the rest of the years. For the drier rainfall scenario, the FSS event loads return to background levels by 600 years after rehabilitation but the values then rose above the equilibrium level in the next 300 years for high rainfall/high FSS load events. An advantage of this modeling approach is that it directly investigates the dynamics of a landform returning to equilibrium. It specifies the number of years taken to reach the equilibrium state in different climate conditions and the dynamics of the landform while attaining stability in each rainfall criterion. It builds on earlier studies [47], which state that the influence of a past process on a geomorphic system is directly proportional to the intensity and duration of the action and inversely to the elapsed time since its occurrence.

The time taken for a landform disturbed by open-cut mining to be restored to its background erosion levels can take centuries. A change in one external variable causes readjustment of all system parameters and thus the geomorphic system responds as an organic whole to changes in the environment [59]. The study of Nair and Bellairs [57] found that the time and also the dynamics of returning back to equilibrium are influenced by hundreds of years of even minor changes in climatic factors. However, from the landform evolution modeling performed with CAESAR-Lisflood, short-term future simulations show that the mine catchment undergoes distinct erosion and deposition in the vicinity of much-disturbed areas like the tailing dam during the initial few years after closure. Later, the landform settles in such a way that there is a general loss of sediment across all elevated areas of the catchment where the mine resides.

Running high-resolution models can take substantial time, but through the coupling of CAESAR-Lisflood 1.9b and HEC-HMS 4.11, the running time could be reduced. There are differences in running time between the CAESAR-Lisflood and the HEC-HMS models. During the modeling of the catchment for future simulations, the hydrology model could run faster and account for rainfall initial losses and continuous losses in the model, which is not available in CAESAR-Lisflood. Rainfall initial and continuous losses are the rainfall that does not result in overland flow. The initial loss represents the volume of water needed to saturate the soil layer at the beginning of the simulation and continuous loss refers to the rate at which precipitation is infiltrated into the soil layer after the initial loss volume has been accounted for. Thus, the HEC-HMS was run, and output data were also used to produce input data for CAESAR-Lisflood for future simulations. This approach helps to fill the gaps in data for input in the models for future simulations. It also reduces the running time. The coupling of CAESAR-Lisflood 1.9b and HEC-HMS 4.11 reduced the running time and therefore the iterative design time of the final landform. It also gives different data outputs like the erosion and deposition features of the landform with an LEM and continuous stream discharge and sediment data with a hydrology model for the study.

This approach thus builds on previous studies and fills some of the knowledge gaps and deficiencies in other monitoring approaches that were previously identified in Section 3. One knowledge gap was that many techniques were site specific. The methodology used in this study can be easily adapted to other tropical mine sites as an assessment tool for landform stability. It requires the measurement of a minimal number of site parameters to assess erosion equilibrium. The approach considers the long-term trends of landform change until it attains stability. It can be used to evaluate the potential impacts of climate change on the erosion equilibrium of a disturbed landform. The approach investigates the quantity of fine suspended sediments leaving the catchment and entering the receiving waters, which is directly linked to the transport of contaminants. Thus, this approach provides insight into the offsite impacts of mining. Apart from the development of an approach to assess mine landform stability, giving an estimate of the time until a rehabilitated landform achieves erosion equilibrium with the surrounding catchment is of value. The approach also determined the impacts of potential climate change on the dynamics of achieving stability and studied the temporal variability of the event fine suspended sediment–discharge relationship.

To conclude, this approach proves that stream-suspended mud can be used as an indicator of landform stability and erosion equilibrium. The FSS-Q relationship is subjected to temporal variation since the denudation rate of the landform decreases over time. The time taken for a disturbed landform to return to equilibrium can take centuries and is influenced by hundreds of years of even minor changes in climatic factors.

6. Broader Context of the Approach

The dynamics of a rehabilitated mine landform acquiring geomorphic equilibrium with the surrounding catchment can be simple, such that the unstable landscape may slowly move to equilibrium conditions and stay at equilibrium. In another scenario, the landform might fluctuate in and out of equilibrium before finally reaching a steady state. The dynamics of a landform reaching equilibrium can be investigated using this method by evaluating the event FSS–discharge relationship across the years, which may not be possible using other techniques of rehabilitation assessment.

FSS event loads are sensitive to changing rainfall patterns on account of climate change. Thus, the impact of climate change on a landform returning to stability can be clearly assessed with this approach. FSS transport is also associated with contaminant transport. Contaminants that are released from a mine catchment due to disturbance attach themselves to FSS and thus it can also give an estimate of contaminant transport from the catchment to the receiving waters. Moreover, the methodology to assess landform equilibrium in this thesis focuses on the offsite impact assessment of mining, which can be of much greater impact than the onsite impacts but is less attended to.

Using several models can aid parameterization for the approach. Nair and Evans [56] explored parameterization of the CAESAR-Lisflood LEM for continuous stream and fine suspended calibration. There were no available continuous site bedrock data pertaining to various particle size distributions, which need to be input into CAESAR-Lisflood for sediment calibration. Turbidity was used as a surrogate indicator of fine suspended sediment, and previous studies on bedrock sediment proportions in stream sediment discharge were used to calculate sediment input in a CAESAR-Lisflood LEM. This can enable this approach to be used where there is limited availability of continuous bedrock sediment data.

When parameterizing the HEC-HMS model for continuous stream discharge and fine suspended sediment calibration, Nair and Evans [32] showed that the hydrology model can run faster and account for rainfall initial and continuous losses in the model, which is not available in CAESAR-Lisflood. Thus, the HEC-HMS was run by itself and also provided input data for CAESAR-Lisflood for future simulations. Combining the two models enabled the filling of data gaps and reduced the run time in a process that can be used in other simulations.

The temporal variation in the FSS-Q relationship could not be determined using past events as long-term site data are not available [52]. However, modeled data enabled long-term simulations [57]. The site data available were for the period of 2004 to 2015 [52]. Site data pertaining to longer time periods of more than a decade could enable the analysis of temporal variation in the fine suspended sediment–stream discharge relationship using real site values. However, the main aim of the methodology evaluation was successful, because the temporal variation of the fine suspended sediment–stream discharge relationship was assessed using simulated data.

Communication with stakeholders about the rehabilitation of and achieving landform stability equilibria on mine sites is aided by this technique. When mining affects the lands of First Nations peoples as in the studies by Nair et al. [32,52,53,56,57], mined land rehabilitation should ensure that the disturbed land is rehabilitated such that it can be entrusted back to and enjoyed by the original custodians of the land. Stakeholders wish to know the time until the rehabilitated landform is stable as in pre-mining conditions. A better understanding of the dynamics of how a mined landform returns to erosion equilibrium with its surrounding landform in different climatic conditions will enable rehabilitation engineers to estimate the timeframe for the process.

7. Limitations of the Approach

This approach can be applied to assess the landform stability of mines in other tropical catchments using the step-by-step approach outlined in Nair and Bellairs´ study [52]. One of the limitations in adapting the approach to another tropical catchment would be data availability. Continuous stream discharge and FSS data are required to establish the event FSS discharge relationship following rainfall events. The approach is best suited for catchments with receiving streams exhibiting continuous stream flow at least during the wet season of the year. Secondly, in order to investigate the catchment disturbance due to mining, it must be ensured that the disturbance is caused by mining alone. It would be difficult to account for FSS spikes on account of mining in catchments where other land use activities are also involved.

A limitation of Nair and Evans' study [56] was the inability to account for changes in catchment vegetation and changes in soil properties over the wet season in the CAESAR-Lisflood model. However, the CAESAR-Lisflood model was later used to assess the impact of the mine site on the downstream development of the catchment landform, focusing on sediment changes and geomorphology. This limitation of being unable to account for changes over the wet season was overcome in Nair and Evans' study [32], where the model (HEC-HMS) could calibrate continuous stream discharge and fine suspended sediment separately in the dry and wet seasons.

The constraint in Nair and Bellairs' study [57] was the much higher processing time taken by the landform evolution model to run at a higher resolution than the Digital Elevation Model (DEM). Running the model at a lower resolution resulted in it taking less time to run but did not account for the major occurrences of erosion and deposition in the catchment. However, running the model at high resolution for a shorter time period revealed that the landform evolved after 20 years with similar trends as those developed in 5 years. Thus, it was not necessary to run the landform evolution model for the long term, which would have taken more processing time since the trends were expected to be similar to short-term landform evolution.

8. Future Research Needs

Several prospects to develop the approach with further research should be investigated. The first would be to determine a technique to automatically determine the boundaries of fine suspended sediment discharge event spikes. This would allow for the development of an application that enables environmental officials to easily input landform values and parameters to assess stability. This can be approached by developing a model that can assess the FSS-Q regression relationship with the site data entered into the model and then compare them with the FSS spikes of future simulations. This will involve identifying the start and end of the FSS spike following a rainfall event and the corresponding discharge from continuous turbidity and discharge data, respectively. This should enable the computation of FSS event load and event discharge automatically by the application, determine a regression relationship between the two parameters, and thus identify FSS spikes.

A greater range of extended rainfall scenarios should be assessed. Extended studies in Nair and Bellairs' study [57] included generating various future rainfall scenarios and then assessing the erosion equilibrium dynamics for these rainfall simulations. It was beyond the scope of that study to run a climate model for the rainfall data, but running a climate model to attain extended and regional rainfall scenarios is an area of prospective research. This could be used to study the effect of climatic changes in rainfall on erosion equilibrium in detail.

The methodology should be tested in a range of other landscapes. The methodology has been tested for a mine catchment in a tropical savannah. Thus, it should be able to be applied to other tropical catchments where a mine resides for land stability assessments. Case studies could investigate other disturbances and other landscape types.

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