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# LANDFORM EVOLUTION MODELLING AND GEOMORPHIC DESIGN PRINCIPLES FOR MINE REHABILITATION LANDFORMS

**Questions and answers**

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## Purpose

A key component of the NSW Resources Regulator's compliance model is to educate and engage the regulated community. This includes helping to exchange information about leading practice associated with rehabilitation landform design.

The Regulator has engaged Associate Professor Greg Hancock, School of Environmental and Life Sciences (Earth Sciences) at the University of Newcastle, to provide advice on the appropriate use of landform evolution modelling and consideration of geomorphic design principles for mine rehabilitation landforms.

Associate Professor Greg Hancock is a recognised expert on the use of landform evolution modelling for the assessment of mine rehabilitation landforms for long-term stability.

Information provided by Associate Professor Greg Hancock has been incorporated into this document. This may assist mine operators in the design and construction of final landforms to achieve long-term stability and fulfill their rehabilitation obligations.

It should be noted that the methodologies referred to in this document are not exhaustive and other landform modelling systems may be available. Mine operators should review all available options and have regard to the circumstances of their mining operations, life-cycle stage and other environmental factors and select the most appropriate option. As part of this process, mine operators are required to undertake risk assessments and comply with relevant NSW legislation.

### Q1: What are the key considerations for landform design for rehabilitation of mine sites and why is this important?

The goal of any mine is to operate with minimal environmental impact. During mine operations, environmental impacts are largely planned and can be controlled. A major issue on any mine site is water management, with all sites having plans to manage and control water for all but the most extreme and unforeseen events. Implicit with this is that any contaminated water and/or sediment will be managed and controlled on-site.

In the post-closure scenario, the goal is for the disturbed area to be rehabilitated such that the area blends in with the surrounds, has minimal off-site impact and is environmentally sustainable. This requires that hillslope shape and length be constructed to achieve these goals.

The first step of this process is to design a landform that is stable and not lead to long-term erosion. This requires that a landscape has hillslope lengths and slopes that ensures erosion will be minimised. A significant issue with designing landforms that are in keeping with the surrounding non-mined landscape is the increased waste volume or bulking as a result of blasting and handling. In many operations the resource removed is only a small fraction of the material moved, leading to an increase in the volume of the waste rock or spoil. As such, it is inevitable that the height of the post-mining landform will be above pre-mining levels.

If erosion from the landscape is minimised or in keeping with that of its surrounds, then the soil profile can be enhanced, nutrients can be stored and be available for recycling, which enables vegetation to be established and maintained. This may also minimise the amount of sediment leaving the site (some soil loss is inevitable) to a rate that is comparable to the surrounding unmined landscape. Consequently, any pollution issues associated with discharges off site (i.e. excess sediment, incompatible sediment geochemistry) is limited.

Where slope length and angles are not suitable, together with a non-ideal growth medium (that is, poor topsoil/subsoil) then the following scenarios may inevitably occur:

- large-scale rilling and gullying
- the erosion rate may be too high for viable germination to set root into the rehabilitated surface
- where significant gullies form, these may depressurise any shallow groundwater system leading to a loss of soil water and nutrients
- where a site has encapsulated suboptimal material within the final landform, the occurrence of gullying may have the potential to expose this material over time.

The overburden at any site can be relatively benign with no harmful characteristics, however, at many mine sites material with a high salt content, acid generating potential or other unacceptable content (i.e. low-grade ore, tailings) needs to be managed. Ideally, the waste stream and construction of the Waste Rock Dump (WRD) need to be designed and constructed with contaminant issues considered. This means that any contaminant needs to be contained and/or encapsulated within the WRD in a planned manner.

Post-mining erosional and landscape stability is key for any subsequent land use to obtain its integration with the surrounding landscape system that has been undisturbed my mining.

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## Q2: How can the performance of long-term stability of landforms be assessed?

Post-mining landforms will be permanent geomorphological features and need to be considered in this context. These structures are geomorphically very different to that of the surrounding undisturbed landscape. Following mine closure, the new landscape is subject to climate and erosional factors as it transitions to become a geomorphic entity. Several knowledge gaps exist as to how these structures perform and integrate into the surrounding landscape. These knowledge gaps include erosional stability, response to climate and climate extremes, design suitability, as well as construction reliability.

Ultimately, the goal is to construct a new landscape that geomorphically integrates into the surrounding landscape and contains the waste material over geological time with little or no maintenance. McKenna and Van Zyl (2020) suggest that closure design be considered for a 1000-year design life for tailings dams.

This requires robust design assessment procedures and the use of models to predict how the final landform design and/or the as-constructed final landform will perform over extended periods of time when considering effects of erosion. The information gained through the use of models can be utilised to refine the landform design prior to construction, as well as undertake further stabilisation works on the constructed final landform to prevent or minimise long-term erosional risks.

## Q3: What are Landform Evolution Models (LEMs)?

There are several modelling tools that can be used to assess erosional stability. First, models such as the RUSLE and derivatives (Wischmeier and Smith, 1978; Laflen et al, 1991) have been widely employed. The RUSLE has been used globally and there is a large database of parameters available for most situations.

Further model developments such as WEPP (Laflen et al, 1991) provide a more sophisticated analysis capability with many additional features, such as plant growth modules, variable climate (via climate file input), as well as being able to be linked to other hillslopes and catchments.

These models, while very reliable and useful when calibrated and used appropriately, predict erosion only and neglect deposition patterns. In addition, they do not dynamically adjust hillslope elevation in response to erosion and deposition.

An advance on the above models are Landform Evolution Models (LEMs). There are numerous soil erosion and landform evolution models developed and employed for a wide range of uses. Originally developed to assess landforms over geological time (Ahnert, 1976), the usefulness of LEMs for engineering applications was quickly realised. Coulthard et al. (2013), Willgoose (2018) and Tucker and Hancock (2010) provide a review of most available models.

CAESAR-Lisflood and SIBERIA are two models that have been used for mine applications. Both models operate using similar principles, however CAESAR-Lisflood operates at hourly time intervals using pluviograph rainfall and provides storm event scale erosion information. However, it is slow to run and has not been used or tested as extensively as SIBERIA. SIBERIA operates at annual time scales and has been tested and employed across a wide range of sites.

The SIBERIA model is the most widely tested and used landform evolution model in the world. It offers unparalleled capability as a design assessment tool and erosion model, together with its ability to assess different surface materials and hydrological conditions. Its speed of operation allows landscape assessments to be conducted over relatively short computing times (i.e. minutes versus days compared to other models) and can be operated over a relatively large domain.

The models are very good at climate risk assessment. In particular, the CAESAR-Lisflood model, with its ability to input pluviograph rainfall, allows enhanced storm frequency and change in rainfall intensity frequency duration to be assessed. Hancock et al (2017a,b) outline several approaches.

The models can assess the effect of biogenic influences, such as disturbance by animals, such as pigs and wombats (Hancock et al. 2015) and require field data on faunal disturbance. The effects of a major tree-throw event (i.e. effects of a cyclone) can also be examined (Hancock et al., 2011).

All LEMs provide information on erosion rate (t/ha/yr) and type (i.e. rilling, gullying), location of erosion and how the landscape visually evolves through time (3D plots).

Both SIBERIA and CAESAR-Lisflood are free and accessible online.

## Q4: Where is the use of LEMs most appropriate for landform design?

LEMs can be used throughout the mine life cycle as the mine operation evolves/changes. Ideally, LEMs should be used in the initial mine planning stage where any issues can be highlighted and managed.

Field data collected from the site (i.e. erosion and hydrology data) during mine operation can be used to refine LEM inputs and therefore assess both current and future designs. This will highlight both strengths and weakness of the current approach and improve rehabilitation. That is, this approach integrates the collection of field data and landform assessment throughout the mine's life cycle and will result in a more robust final landscape.

There are no size or scale limitations to the use of LEMs. They have proven to be reliable for small areas (i.e. <ha) as well as several kilometres$^2$. However, LEMs are most suitable for sites where the disturbance is large and complex and where the post-mining landscape shape is distinctly different to that of the surrounding landscape.

LEMs are useful for the following:

- large and complex landscapes that sit proud above the surrounding landscape
- sites that integrate a waste rock dump into a surrounding landscape feature, such as a hill
- waste rock dumps and tailings facilities that contain suboptimal material
- assessment of cover designs (i.e. tailings cover and or cover over PAF material).

## Q5: Besides LEMs, what other methods can be used to model long-term landform stability?

Models such as the RUSLE and WEPP are extremely useful tools with which to assess erosion. Both are well tested and extensively used for mining applications. In particular, the RUSLE has a large database of parameters available. WEPP is somewhat more sophisticated than the RUSLE in that it can use climate files and link hillslopes and channels so that whole landscape can be modelled. However, neither model dynamically adjusts the landscape in response to erosion and deposition. Both provide information on erosion only.

The Blue Book provides a tremendous wealth of information for landscape design and management that has been largely developed for agricultural and engineering applications, where sites will be continually used and maintained (i.e. cropping systems). The principles are sound, and when used correctly with an understanding of the underlying materials the information, provides sound design guidelines.

However, utilising the Blue Book provides an engineering solution with no consideration for hillslope shape and curvature. The resulting landscape generally consists of linear hillslopes, contour banks and engineered channels. Contour banks will ultimately erode and fail and engineered drains will ultimately fill with sediment. Therefore, a landscape constructed with linear slopes and contour banks will ultimately find its own geomorphic path.

The use of the Blue Book design guidelines is appropriate if the landscape will be continually maintained (i.e. contour banks will be continually maintained or used for agriculture where the new owner will maintain the system). The guidelines are generally not suitable for walk-away.

## Q6: What issues should be considered when assessing landform design?

Issues to be considered in terms of design and site management are:

- material characterisation
- observation
- field measurement
- surveying
- field plots and
- record keeping.

**Understand the characteristics of materials**

Basic soils assessment of waste rock and covers (i.e. topsoil) is essential. There is no point having a very good landscape design if the underlying waste is hostile and there is insufficient topsoil (or alternative) for cover. It is important to note that topsoil quality varies and there is no point using if it is suboptimal and can't be ameliorated.

**Observation**

Conducting site inspections through each phase of rehabilitation is important to identify early signs of long-term stability issues such as patchy vegetation establishment, rilling and gullying. However, it should be noted that erosion is likely to occur in newly constructed landforms. The question is, what is acceptable? If there are some rills and gullies in drainage lines, are they going to evolve to something larger? They may be a short-term feature that are difficult to avoid.

Importantly, a mine will need to have trigger action response plans in place to enable early intervention measures to be adopted to minimise the potential for long-term stability issues.

**Field measurement**

Field monitoring locations should be set up on the rehabilitated landform with photo points and erosion pins to monitor material loss through erosion. Erosion pins are cheap and easy to install and measure (Hancock and Lowry, 2015). They can provide a cost-effective tool with which to quantify erosion rates and trajectory.

**Surveying**

Surveying is also typically used to quantify erosion rate and trajectory.

Light Detection and Ranging (LiDAR) has become a common tool on most mine sites. High resolution LiDAR is a very effective tool with which to quantify erosion. However, it is vital that control points are included in the LiDAR survey to guarantee accuracy.

Other methods such as laser scans and digital photogrammetry are also very useful in areas where there is no vegetation, as neither method can see through vegetation.

These methods can become part of the regular mine survey and used to measure and or assist in the validation process as to whether a landform is likely to be stable in the long term.

**Field plots**

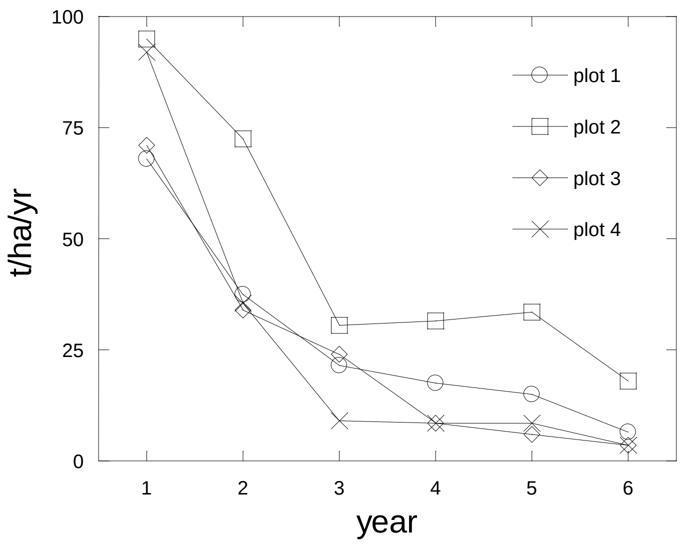
Given that mines may operate for many decades, it is of considerable benefit to set up test plots early in a mine's life. While the materials used on these early plots will likely be different to those during the mine's life, they will provide essential information such as:

- demonstrating a reduction in erosion rates over time
- the performance of vegetation strategies
- quantifying sediment transport and hydrology data.

Data from field plots can be used for calibration and validation of LEMs.

Post-mining landscapes rapidly evolve. Designing a landform based on parameters derived in the first-year post-construction will result in a landscape that is likely overengineered (refer to Figure 1). Similarly, using flumes or rainfall simulators to generate parameters only provides data on the present materials and does not take into account weathering and armouring. Field plots allow the determination of defensible parameter sets that can be used to better represent the long-term landscape behaviour. Therefore, this will save money for the mining company and produce an enhanced environmental outcome.

**Figure 1**. Erosion rates from a post-mining landform




### Record keeping

A major issue on most mine sites is the record keeping of rehabilitation. Record keeping on soils and waste rock properties, ameliorants and fertiliser used, seeding and surface preparation (i.e. ripping), weather and soil moisture conditions should be a key objective at each mine.

Retaining knowledge on site to evaluate successes and failures is essential to ensure continual improvement and successful rehabilitation.

## Q7: What are the key steps when using LEMs for landform design?

LEMs provide XYZ coordinates of the evolving landform through time and landscape outputs that can be visualised in any GIS/visualisation software.

Most LEMs are run at annual time steps. However, the CAESAR-Lisflood model can be run at hourly time steps, with hourly outputs of the evolved landform if that level of detail is required.

The SIBERIA model operates at annual time steps with output at the same annual time step. However, the model can be calibrated to run at shorter time steps if required.

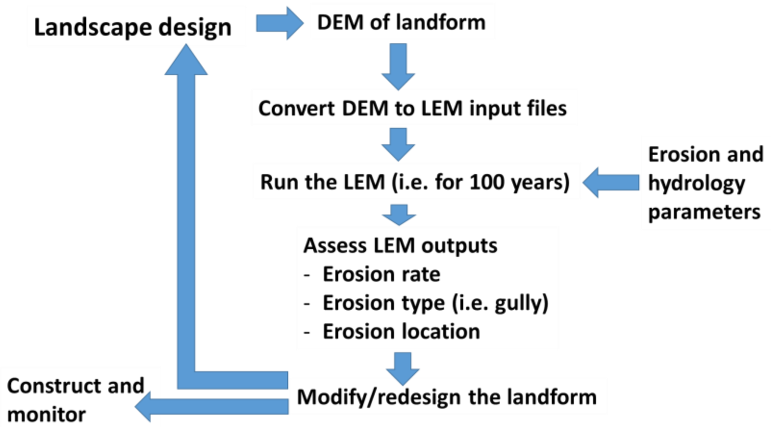
All LEMs need a digital elevation model (DEM) to represent the landform to be modelled. The DEM must be sufficiently accurate and detailed, such that all features that control water and sediment flux (i.e. contour banks, sediment basins) can be identified and factored into the LEM.

LEMs also require hydrology and sediment transport data that represents the mine's surface materials and climate. These parameters are site specific, with the highest reliability obtained from field plots and hillslope data. However, flumes and rainfall simulators can be used to generate input parameters.

Generic parameter data sets are available for most areas and materials, however any resultant model prediction is a guide only.

From the evolved landform, erosion type (i.e. sheetwash, rill, gully) can be observed, where the erosion is occurring and erosion rate quantified. The process for using a LEM is outlined in Figure 2.

**Figure 2**. Process diagram for using a LEM




## Q8: What are the limitations for LEMs?

LEMs are similar to any model used. Poor quality inputs produce poor quality outputs.

There are two major issues with LEMs:

- The DEM must be sufficiently accurate and reliable to represent the landscape and features of interest that control water and sediment flux.
- Hydrology and sediment transport parameters that represent the surface and landscape are required.

If the model is calibrated using field data from a new surface, then the parameters will likely be different to that of a surface that has been exposed for several years and has vegetation, as well as weathering and armouring processes occurring.

## Q9: What data and other resources are typically required for LEMs?

Most assessments of post-mining landforms use generic hydrology and sediment transport parameters given the limited availability of site-specific data. These generic data sets are available with the model downloads and associated websites.

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Hydrology and sediment transport parameters can be reliably determined using laboratory flumes and/or rainfall simulators. However, parameters derived by such methods do not incorporate weathering and armouring or vegetation establishment and growth.

It is unusual for a mine to have site specific field data as it is considered somewhat time consuming and expensive to obtain.

An approach to addressing the lack of field data would be for the mining industry to establish a series of long-term field plots to better monitor and understand:

- hydrology and sediment transport parameters
- how parameters change through time (i.e. weathering/armouring)
- vegetation establishment over time and quantifiable influence on points one and two above.

These plots, if setup correctly, would provide defensible regional data that can be used by industry and regulators with site-specific data acquired as needed.

There are several questions to answer to ensure LEM outputs are accurate and reliable. These include:

- How were the model/s calibrated (i.e. hydrology and sediment transport parameters)?
- All models require a DEM for landscape input. Is this appropriate and does it capture all relevant features?
- Model output assessment:
    - gullies – how deep and where (important for tailings, PAF)
    - erosion rate
    - off-site movement of sediment.

## Q10: What is geomorphic design?

A common practice for new mine landscapes is to construct standalone/isolated Waste Rock Dumps. They are constructed in different physiographic locations to simple linear designs (with a number of ‘lifts’ of usually 10-metre steps) to achieve maximum economic efficiency. This efficiency is a monetary cost issue, where the dump is usually located close to the pit so that cost, travel time and distance to transport the waste material is minimised. However, for the majority of these landscapes, they are stand-alone and out of keeping structures with no geomorphological link, both functionally and visually, to their surrounds. To manage runoff, control structures, such as contour or graded banks and engineered channels, are constructed. There is also little consideration as to how these landscapes will mature through time.

Geomorphic design is a method where a landscape is constructed based on a set of geomorphic rules such as Strahler stream order, hillslope length and curvature and stream length and curvature. These rules are derived from an analogue site which is deemed to have properties suitable for the post-mining landform. The goal is to mimic the geomorphic patterns of nature to provide an erosionally stable, ecologically functional and aesthetically pleasing reconstructed landform.

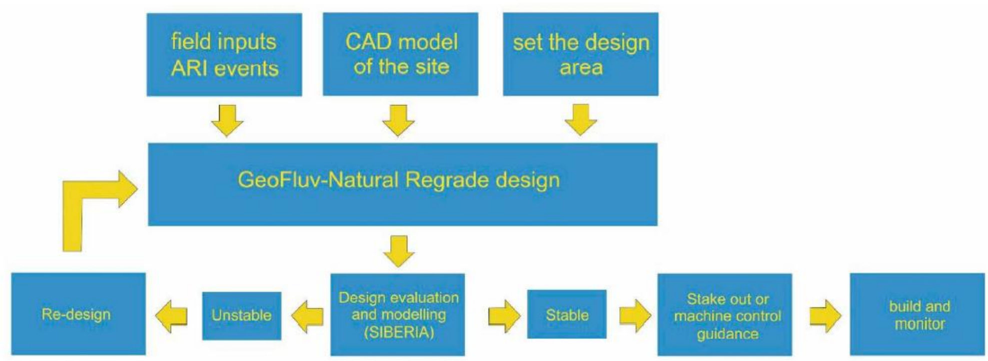
Geomorphic design can be done by any practitioner using computer aided design tools (i.e. AutoCAD) without the need for specialised design software. However, in recent years, software such as GeoFluv has been developed to undertake geomorphic design.

The method used by GeoFluv requires a DEM of the site and the project boundaries. Rainfall data is required to assess runoff from the new design. The position of streams, distance from divide, hillslope length and curvature are applied over the landscape. Subsequently the landscape design can be adjusted while keeping in mind material volume and footprint constraints.

## Q11: How can geomorphic design be assessed by LEM?

Once a design is finalised, it can be assessed using a LEM (such as SIBERIA). This will highlight any design issues, which are then rectified in GeoFluv (or other design tool) and reassessed in a LEM. Using this process allows an optimised design to be built. The process is outlined in Figure 3.

**Figure 3**. Geomorphic design method using the Geofluv approach




## Q12: Are there limitations for use of geomorphic design?

Geomorphic design software is a significant advancement in post-mining landscape design. However, there are several limitations with the approach.

What is used as a geomorphic analogue to guide landscape reconstruction becomes an issue. Trying to replicate the surrounding undisturbed landscape will be impossible, as the physical and chemical structure of the reconstructed landform will be very different to that of the pre-mine landscape and surrounds. Furthermore, there will be no reconstructed mine sites of sufficient age from which long-term geomorphic attributes or landscape trajectory can be determined from.

One option is to seek information from the surrounding natural landscape. While the natural landscape has physical and chemical characteristics very different to the new landscape system, the hillslope curvature, slope length and angle, channel profiles will provide a much more natural and robust design. That is, there are very few linear hillslopes in nature with contour banks.

At some sites geomorphological analogues have been sought. The ERA Ranger mine in the Northern Territory, Australia has sought a potential analogue site, Tin Camp Creek, that is geologically and geochemically similar to that of the Ranger mine waste.

A further limitation is that the geomorphic designs require some form of independent assessment. Assessing a geomorphically designed landform using a LEM is not commonly undertaken. However, this provides a guide as to how the landscape may perform in the long term.

The design of landforms using a geomorphic approach is not landscape architecture, which some believe it to be. While an aesthetically pleasing landform may result, this is not the goal. The goal is to construct a geomorphically robust landform that minimises soil and water loss and optimises ecological function while integrating with the surrounding undisturbed landscape.

Further considerations include footprint and volume constraints. In many cases, it may be difficult to design a landform using geomorphic principles as the volume of material to be managed may require a tall structure. There are several options that may be needed, such as the construction of rock lined channels (which are problematic in their own right and expensive to construct) and sediment basins. Or a mine must accept that initially higher rates of erosion will occur (i.e. gullies) which will have to be managed until the site stabilises.

Ultimately, any constructed landform will self-evolve to a more stable form in response to the initial landform, materials and climate. Geomorphic design works with the materials and climate to produce a stable landform.

In summary:

- Geomorphic design is an aspirational approach. However, there may be areas where drainage control is needed, such as constructed rock line channels to stabilise the landform initially until vegetation is established.
- Some sites may not be amenable to geomorphic design due to site constraints.
- Analogues for geomorphic design are not easy to identify. Post-mining materials are very different to that of the natural (or analogue landscape).
- The best option is to create a landform in a geomorphic design package and test in a LEM using site-specific parameters.

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## Q13: What would be considered current leading practice for LEMs?

Leading practice for the employment of LEMs would be:

- the site has a long-term field plot/s that are collecting erosion and soil loss data
- this data is used to develop site specific hydrology and sediment transport parameters
- these parameters are then used to assess both current and proposed landscapes as the mine operates and evolves
- use the LEM through time as the mine changes to provide guidance for optimal landscape design
- the LEM takes into account parameter change (i.e vegetation growth).

## References

Ahnert, F, 1976. Brief description of a comprehensive three-dimensional model of landform development, Zeitschrift fur Geomorphologie Supplement Band, 25:29–49.

Coulthard TJ, Neal JC, Bates PD, Ramirez J, de Almeida GAM, Hancock GR. 2013. Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution, Earth Surface Processes and Landforms, https://DOI: 10.1002/esp.3478

Hancock GR, Lowry JBC. 2015. Hillslope erosion measurement—a simple approach to a

complex process, Hydrological Processes, DOI: 10.1002/hyp.10608

Hancock GR, Evans KG, McDonnell JJ, Hopp L. 2011. Ecohydrological controls on soil erosion and landscape evolution, Ecohydrology, DOI: 10.1002/eco.241

Hancock GR, Lowry JBC, Dever C, Braggins M. 2015. Does introduced fauna influence soil erosion? A field and modelling assessment, Science of the Total Environment 518–519, 189–200.

Hancock, G.R., Verdon-Kidd, D., Lowry, J. B. C. 2017a. Sediment output from a post-mining catchment – Centennial impact using stochastically generated rainfall, Journal of Hydrology, 544 (2017) 180–194

Hancock GR, Verdon-Kidd D, Lowry JBC. 2017b. Soil erosion predictions from a landscape evolution model – An assessment of a post-mining landform using spatial climate change analogues, Science of the Total Environment 601–602 (2017) 109–121

McKenna G, Van Zyl D. 2020. Chapter VIII Closure and reclamation, in Oberle B, Brereton D, Mihaylova A. 2020. Towards Zero Harm: A Compendium of Papers Prepared for the Global Tailings Review. St Gallen, Switzerland: Global Tailings Review.

https://globaltailingsreview.org/ (accessed November 2020).

Laflen, J M, Elliot, W J, Simanton, J R, Holzhey, C S and Kohl, K D, 1991. WEPP soil erodibility experiments for rangeland and cropland soils, Journal of Soil and Water Conservation, 46(1):39–34.

Supervising Scientist 2018. Landform Stability — Rehabilitation Standard for the Ranger uranium mine (version 1). Supervising Scientist Branch, Darwin, NT. http://www.environment.gov.au/science/supervising-scientist/publications/ss-rehabilitation-standards.

Tucker, G and Hancock, G R, 2010. Modelling landscape evolution, Earth

Surface Processes and Landforms, 35:28–50.

Willgoose, G. 2018. Principles of Soilscape and Landscape Evolution, Cambridge University Press, Cambridge, UK, 356pp.

Wischmeier WH, Smith DD. 1978. Predicting rainfall erosion losses-A guide to Conservation Planning. US Department of Agriculture, Agriculture Handbook No. 537.2

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