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Evaluation of the water erosion prediction project model – validation data from sites in Western Australia

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Abstract

Computer simulations of runoff and erosion are a key element in the design of stable waste dump outer batter profiles. The Water Erosion Prediction Project (WEPP) model is used to develop erosionally stable landform batter surfaces. Although the WEPP model has been widely validated elsewhere, there is a perceived need to similarly validate the model for mine site conditions. Erosion monitoring data collected on landforms for which model parameters are known can be used for two primary purposes: a) to demonstrate that erosion rates are consistent with site targets; and b) to validate and more precisely calibrate the erosion model used in landform design, enabling continuous improvement in the design process.

Model validation techniques are discussed and validation data for several landforms are presented. In general, cumulative erosion rates measured since completion of construction show good agreement with predicted erosion rates. The data have provided validation of the landform design process used; confidence in the surface stability of existing landforms that have been constructed; refinement and improvement in the design process; and a means for continual improvement in landform rehabilitation methods.

1 Introduction

Waste landforms are expected to remain within the landscape once mining has finished, and it is the community's expectation that these landforms are appropriately rehabilitated. A fundamental rehabilitation criterion for closure of a mine waste landform in Australia is the establishment of a stable land surface (i.e. one with low long-term erosion rates) that is able to support vegetation. This mine closure objective is often at odds with the operational requirements of waste landforms while the mine is in production. Operationally, waste landforms that are steeply sloped and very tall are most cost effective to construct and require lower environmental bonds due to a smaller footprint. From the perspective of rehabilitation however, landforms that are steeply sloping and very tall can have very high erosion rates and are unlikely to be stable in the long-term. In this paper, stability is defined as the erosional stability of the land surface, a function of both rill and interrill erosion processes.

A defensible means of balancing the rehabilitation and operational objectives is required. Often the duration of mining is short compared to the period of time required to find an appropriate final landform configuration by using field-based trials. Predictive modelling can overcome this problem by examining the various factors of surface stability such as slope gradient, slope length and cover material. The Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) is a tool that can be widely applied to define stable final landform shapes by examining the relationship between slope, climate, and materials to arrive at landform shapes with low erosion potential. Knowing these shapes early in mining operations means that materials can be placed during dump construction to minimise costly reshaping during rehabilitation.

All models require validation to ensure that the way they represent the physical processes in question are appropriate. Similarly, when using the WEPP model to predict runoff and erosion (and hence surface stability), it is important that the model is validated in order to have confidence that the model's input parameters adequately represent the system being modelled. The correlation between the model's outputs

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and actual observations determines how well the model's assumptions and internal equations are predicting soil erosion at the slope scale.

Although the WEPP model has been widely validated elsewhere (particularly in the agricultural sector), there is a need to similarly validate the model for mine site conditions. This paper briefly describes the WEPP model, discusses validation of the model, provides validation data from studies conducted both in Western Australia and elsewhere, and outlines the usefulness of erosion data for improving landform rehabilitation methods.

2 The WEPP model

The WEPP model was developed by the United States Department of Agriculture's (USDA) Forest Service, Agricultural Research Service and Natural Resources Conservation Service and the United States Department of the Interior's (USDI) Bureau of Land Management (Flanagan and Nearing, 1995). The WEPP model is the result of 10 years of research by many USDA and USDI scientists, plus co-operators from several universities and foreign countries.

It is a distributed parameter, continuous simulation erosion prediction model. Input parameters include information about rainfall, soil, plant growth and decomposition, tillage implement characteristics and slope shape. It is a daily time step model, and each day WEPP simulates runoff and erosion from a given slope shape based on the initial soil hydrological conditions on the day, characteristics of the rain event that may occur on the day, and soil erodibility and infiltration characteristics. As a daily time step model, it is capable of inputting individual storm events and predicts (among other things) runoff and erosion on an event basis. As such, it is significantly more powerful than either the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) or the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1996) in predicting erosion, as these models are designed to consider erosion only on a long-term (mean annual) basis.

WEPP embodies the fundamental concept that erosion is a process of both detachment and transport. If a rain event occurs, it may or may not cause a runoff event. If runoff is predicted to occur, soil loss, sediment enrichment in runoff, sediment delivery off-site and sediment deposition are calculated for each event.

WEPP is able to input complex slope shapes, including linear, concave, convex, and convex-concave profiles. The required soil parameters are independent of slope profile and climate, and this enables the model's user to predict the rate of erosion of a particular soil or slope forming material for a wide variety of slope shapes, gradients, and heights. WEPP can predict both erosion and deposition, unlike the USLE and RUSLE.

WEPP can be used to assess erosion potential for extreme rainfall events. When coupled with the RUSLE, it can also be used to assess the impacts on runoff and erosion of the addition of rock, tree debris, or vegetation to the land surface.

3 WEPP model evaluation

3.1 Importance of validation

When models are used in a predictive capacity, validation is needed to demonstrate that the model's internal equations and assumptions adequately represent the complex processes that occur when runoff is generated and soil is eroded. Further, validation also serves to confirm that the parameters used to predict runoff and erosion provide a well calibrated model, and that the predicted erosion rates reflect reality.

Validation of the WEPP model in terms of its equations and assumptions are detailed in the model's manuals and in published literature and will not be discussed further. Validation of the WEPP model's predictive ability will be discussed below by comparing measured erosion with that predicted by WEPP using information on slope shape, management practices, and climate.

3.2 Evaluation techniques

Evaluation of an erosion model essentially requires two things:

1. Observed erosion data for a given period of time.
2. Model-predicted erosion data for the same period of time.

3.2.1 Measuring erosion

Erosion is typically observed either by measuring the eroded sediment that leaves a slope section of known plot size, or by measuring the change in the surface shape and estimating the associated mass of eroded sediment, again for a known plot size. Assessment of erosion by measuring changes in surface shape can be performed using erosion transects perpendicular to the direction of water flow, high resolution aerial photography, or laser-based techniques.

Assessment of erosion by measuring eroded sediment requires the establishment of a large-scale erosion plot. Large scale plots are needed to ensure that all erosion processes can occur (e.g. rill erosion requires increased flow shear stresses to be initiated) and that eroded sediment is not exhausted from smaller-sized plots (leading to underestimates of erosion potential). Over approximately the last two decades the methodology used for erosion plot studies across Australia has evolved to a distinctive and consistent technique (Figure 1). The technique involves:

1. Trapping bedload sediment in a sedimentation trough at the base of the plot.
2. Capturing suspended sediment laden runoff through tipping buckets to measure runoff volumes for each event.
3. Sampling suspended sediment laden runoff using flow splitters to measure suspended sediment loads.

Figure 1 Example of erosion plots installed on a batter slope

Importantly, this approach allows for the separation of bedload and suspended sediment. It is suspended sediment that poses the greatest potential for off-site impacts, and is also critical in determining the efficacy of sediment detention systems. The data that are produced are a direct measure of soil loss rather than estimates based on changes in surface shape. Data can be collected on an event basis rather than over long periods. The efficacy of erosion plots is unaffected by the presence of vegetation, unlike indirect techniques such as laser scanning or high resolution aerial imagery. Compared to other methods, installation of plots can be initially costly. However, once installed they can remain functional for many years, and become a cost-effective means of sourcing measured runoff and erosion data.

Usefully, other monitoring techniques commonly used for vegetation monitoring utilise transects that can also be used to assess erosion. In the case of Landscape Function Analysis (LFA) (Tongway and Hindley, 2004), these transects (those that run across the slope) are already established to assess erosion trends and the data can be further used in conjunction with WEPP model predictions of erosion to calibrate and validate the model outputs. Erosion transects are typically at least 50 m wide, and can be established at multiple points along the slope. Their position should reflect the required erosion data. For example, an erosion transect could be positioned below a zone of tree debris placed on a batter to control erosion in an area predicted to be susceptible to erosion (Figure 2). Alternately, for complex shapes, transects could be positioned to collect data from slope sections of different gradients. The transects are monitored as part the regular monitoring programme, and measurements of rill shapes and counts are taken and used to estimate soil loss. The transect method assumes that the majority of erosion occurs within concentrated flow lines (rills or gullies), and that only a minor amount of erosion occurs via sheet erosion. Reported values of the ratio of rill erosion to total erosion do vary, but Govers and Poesen (1988) report rill/gully erosion of medium textured soils with little rock typically accounting for >70–90% of total erosion. Poesen et al. (1996) reports that 80–83% of total sediment produced from intensely cultivated small catchments is derived from ephemeral gully systems on stony sandy loam soils in Portugal and Spain, and 60–80% for gravelly loam soils in Arizona, USA.

The measured erosion can then be compared with the predicted erosion rates from WEPP, provided climate data for the monitoring period and the relevant erodibility parameters are also used.

Figure 2 Zone of tree debris placement in response to erosion modelling

Aerial photography and laser-based techniques can also be used to capture a high resolution, three dimensional model of the eroded surface. A series of images are taken at regular intervals (annually) and then compared to determine rates of soil loss and/or deposition. Data acquisition is rapid, but the technology is expensive and data processing is slow in comparison with using transect methods. These methods are confounded by occlusion caused by surface vegetation, and the tortuosity and undercutting (gully side walls) of erosion features. Changes in elevation via settlement and consolidation also affect the accuracy of erosion measurements using these methods.

3.2.2 Calculating erosion using WEPP

Prediction of erosion using WEPP requires inputs relating to climate, slope and land management, and soil surface materials. Soil parameters are sourced through basic laboratory-based characterisation (particle size distribution, organic matter, cation exchange capacity) and through application of simulated rain and overland flow either in the laboratory or the field to derive erodibility parameters. Soil parameters are independent of slope and climate. Climate data for the same period over which erosion from the slope was observed can be sourced from a mine site's weather station (sub-daily data are required). Slope and land management parameters can be set, based on characteristics of the slope in question.

Once the input parameters are set, the WEPP model can be run to predict event-based, monthly, or annualised runoff and erosion. The format of the predicted erosion output depends on the type of validation data measured. Transect or digital data are typically compared against annualised erosion rate predictions. Erosion plot data can be compared to event-based, monthly, or annualised erosion rate predictions.

4 Validation studies

4.1 Review of existing validation studies

The WEPP model has been widely tested against measured data. Validation studies have largely focussed on agricultural settings in the United States of America, Australia and China.

Ghidey and Alberts (1996) report the comparison of WEPP output and measured data for eleven years of runoff and soil loss measurements collected from 40 silty loam agricultural plots subjected to a range of treatments in Missouri, USA. WEPP was parameterised using the model's internal soil erodibility and hydraulic conductivity prediction equations that can be used in the absence of measured parameter values. The model was observed to systematically over-predict erosion for years with >200 mm rain, and under-predict erosion in years with <100 mm rain. However, when plots were modelled with WEPP parameters relating to vegetation and consolidation constrained (i.e. no vegetation, and a surface not subject to consolidation), model prediction of erosion when compared with observed data was considerably better. These results indicate that the WEPP model's internal procedures to estimate effects of vegetation and soil consolidation (in the absence of actual data) tend to introduce error. WEPP can be more accurately used to predict erosion when soil-based parameters are derived from consolidated surfaces rather than allowing the WEPP model to estimate these affects.

The predictive ability of WEPP was assessed by Nearing and Nicks (1998) for 64 erosion plots on a wide range of soils with a combined total of 544 years of erosion data in the USA. It was found that WEPP was able to predict erosion as effectively as other available erosion models (USLE and RUSLE), and that comparisons of observed and predicted erosion data were reasonable (Figure 3).

Yu and Rosewell (2001) validated WEPP on slopes ranging in length from 21–62 m in Gunnedah, New South Wales. Climate data were sourced from the site and erodibility parameters were derived using standard procedures outlined in the WEPP model's manual. WEPP was used for bare fallow and annual wheat crops while employing both the actual cultivation management practices for the trial period (7 years), and the typical management scenario (TMS) that represents historical practice. WEPP was shown to work extremely well when predicting the relationship between annual runoff and soil loss from bare plots, with a prediction efficiency for both runoff and erosion of 0.97 when the actual management practices were considered (Figure 4). Prediction efficiency with TMS was 0.98 and 0.94 for runoff and soil loss respectively. The predicted erosion rates in this study did, however show that WEPP systematically over-estimated erosion. When this fact is coupled with the high prediction efficiency stated above and that the model's input parameters were not calibrated, the over-estimation can be attributed to errors in the input parameters rather than the ability of the model to predict erosion. This highlights that WEPP is capable of modelling erosion reliably provided calibrated input parameters are used.

Yu et al. (2000) found significant improvements in erosion prediction when calibrated parameter values were used, rather than when parameters were estimated using the internal parameter formulas within the WEPP model. In this 3 year study of soil loss from a pineapple plantation, a bare slope was measured to have an annual soil loss of 199 t ha^{-1} y^{-1}. Erosion predicted using internal equations to set soil erodibility parameters was 7.7 t ha^{-1} y^{-1}. When the soil parameters were modified such that the sum of squared errors was minimised, predicted erosion was 149 t ha^{-1} y^{-1}, which was markedly better than predictions made using the uncalibrated parameters. Yu et al. (2000) also state that test statistics used to characterise model performance all lie in the acceptable range for both runoff and soil loss.

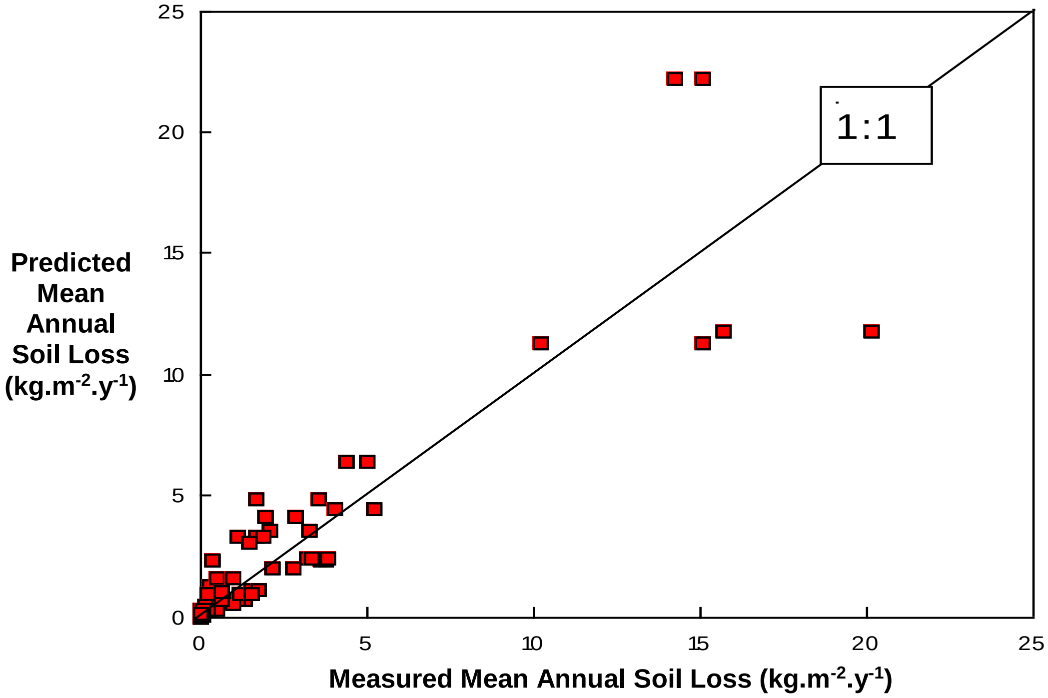

Figure 3 Comparison of predicted and measured average annual soil loss for 64 erosion plots in the United States of America (from Nearing and Nicks, 1998)

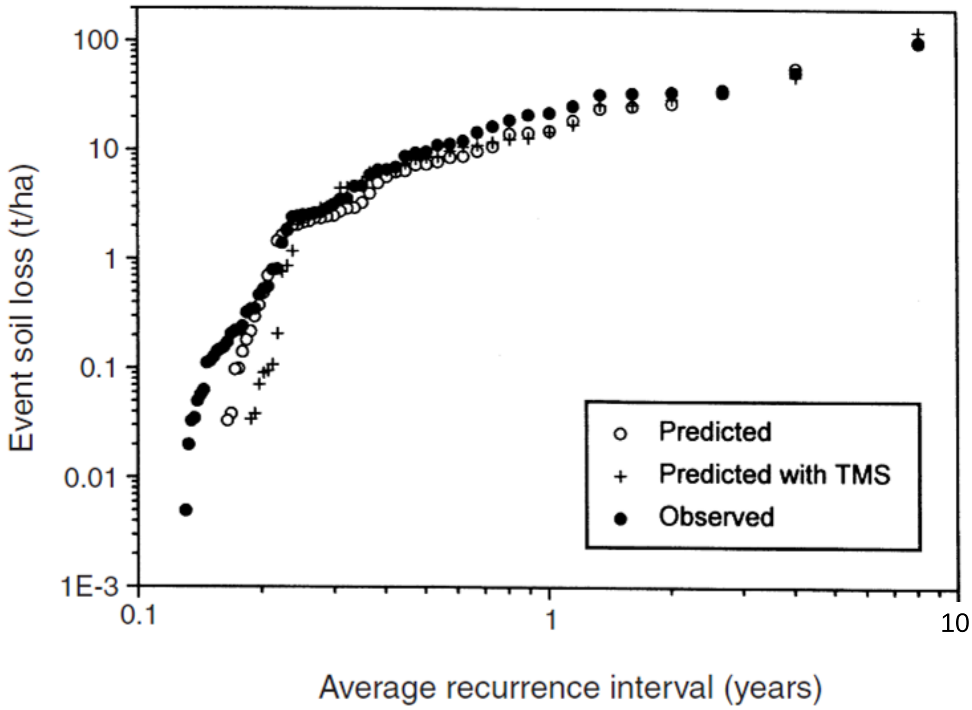

Figure 4 Predicted and observed event soil loss as a function of the average recurrence interval for a bare soil plot (from Yu and Rosewell, 2001)

Unpublished experiments on steep slopes in China have shown that the WEPP model accurately predicts soil losses from slopes with gradient in the range 9–58%, and various slope lengths up to 40 m (R.J. Loch, 23 July 2012, pers. comm.).

Other validation efforts (for example: Liu et al., 1997; Zhang et al., 1996; Tiwari et al., 2000; and Nearing et al., 1998) also show that in general WEPP performs well, given that no erosion model is expected to be extremely precise (Nearing et al., 1999). Inaccuracies in erosion predictions are typically attributed to uncalibrated input parameters and not the inherent predictive ability of the model. Tiwari et al. (2000) found that WEPP performed as well as or better than the USLE at 85% of the 20 USLE-type plots assessed. These sites contained the equivalent of 1,594 plot-years of runoff and erosion data from natural rain events. This model performance was observed for WEPP predictions using uncalibrated soil parameters. This is an excellent result considering that comparisons of WEPP soil loss predictions (from uncalibrated soil parameters) with those made by the USLE and RUSLE (both calibrated to soil) were biased in the USLE's and RUSLE's favour (Laflen et al., 2004). Tiwari et al. (2000) further indicated that calibration of the soil parameters would have greatly improved WEPP predictions. Bjorneberg et al. (1999) evaluated the WEPP model on furrow irrigated plots where calibrated parameters for hydraulic conductivity, critical shear and rill erodibility were used in model predictions of soil loss. Good agreement was found between observed and predicted erosion (71% of data lying within the 95% confidence interval bounds), and it was recommended that calibrated soil parameters must be used in order for WEPP to be used effectively for predicting erosion from irrigated areas. In a review of many WEPP evaluation studies, Laflen et al. (2004) noted that WEPP soil loss predictions using uncalibrated soil parameters compare very well with predictions made by the USLE or RUSLE and that improvements in parameter estimation would improve model predictions.

4.2 Validation of erosion from waste dump batters on WA mines

Erosion monitoring data have been sourced from a total of 11 locations on seven landforms across Western Australia. Currently, an additional 25 locations are being established by Landloch Pty Ltd on landforms across Western Australia, as well as other areas in Australia and overseas.

The Western Australian data on soil loss were collected using erosion transects 30–50 m wide, located at both the upper and lower sections of waste dump batters. Batter shapes assessed include both linear and concave cross-sectional profiles. Slope gradients assessed are consistent with the steep slopes commonly used for mining landforms. Surfaces assessed include loamy soils, clay soils and rocky sandy loam soils. The ages of the batters (years after slope completion) range from 3–7 years. In some cases, the slopes have been designed to minimise erosion, whereas others represent slopes with high erosion rates for which attempts to minimise erosion have not been made. As such, slope conditions range from minimally eroded to heavily eroded surfaces. WEPP model parameters used to predict erosion were derived from both field-based and laboratory-based measurements and can be considered calibrated to the surface materials present.

Cumulative erosion rates (since completion of batter construction) predicted by the WEPP model for these 11 locations are shown in Figure 5. The measured cumulative erosion rates show excellent agreement with rates predicted by WEPP (though this was not tested statistically). Given that these data include predictions from both the upper and lower section of landform batters, WEPP is shown to be able to suitably predict changes in erosion rates with changing slope lengths and gradients. Model output can adequately represent both runoff accumulation down the slope, and flow concentration across the slope.

The accuracy of the predictions shown in Figure 5 also indicates that the methods used to derive the essential model parameters are producing well calibrated model results. This gives confidence that accurate calibration of the WEPP model has been consistently achieved using Landloch's laboratory and field-based methodologies.

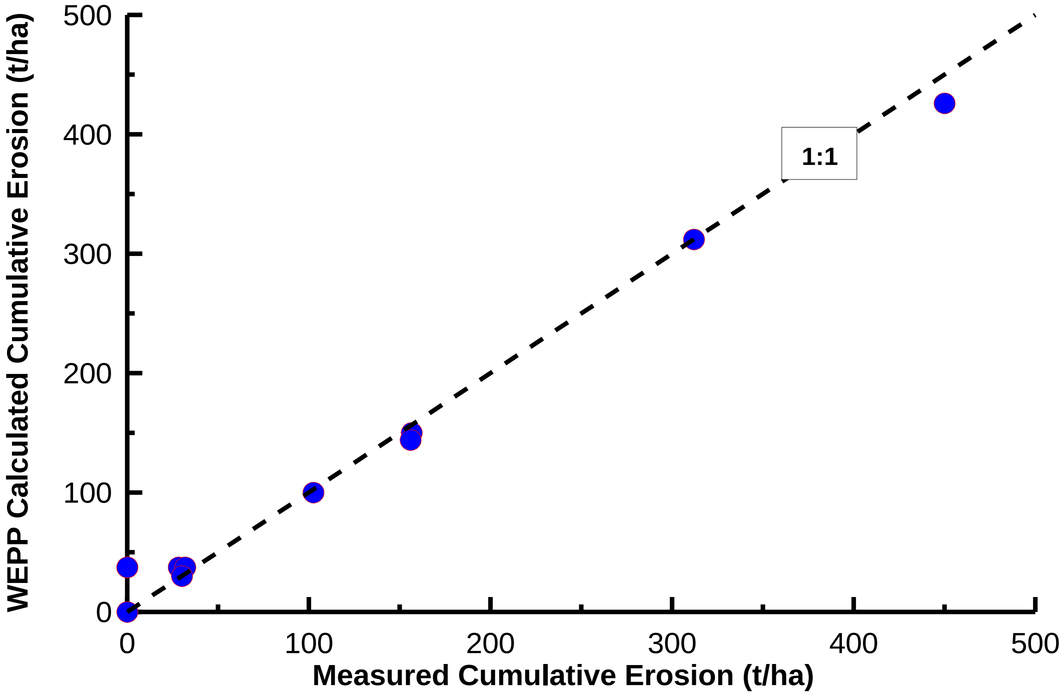

Figure 5 Predicted and observed cumulative erosion rates for 11 batter slope locations in Western Australian mine sites

4.3 Other useful observations

4.3.1 Unconditional performance bond reduction

Within Western Australia, unconditional performance bonds are required to be lodged with the State prior to approval of a mining operation. Bonds are intended to provide the State with funds to enable rehabilitation of a site if a tenement holder fails to meet their environmental conditions (DMP, 2004). Most waste landforms in WA (being higher than 25 m) are deemed to be high risk structures, and bonds have historically only rarely been reduced.

Several waste landforms included in the erosion monitoring data shown in Figure 5 achieved full or partial environmental bond reduction (Howard et al., 2010) within 5–7 years of completion of rehabilitation works. Integral to the process that lead to the bond reduction was the ability of the tenement holder to demonstrate to the regulators that landform surface stability could be achieved. Relinquishment of bonds so quickly is viewed by the authors, the tenement holder in question, and the regulators as a significant achievement, and evidence that the Western Australian regulators (in this case) viewed the approach favourably.

4.3.2 Rehabilitation of the Wiluna tailings storage facility C

The WEPP model was used to design the Tailings Storage Facility (TSF) C at the Wiluna Gold Mine in 2001. WEPP erodibility parameters were derived using laboratory-based procedures developed by Landloch Pty Ltd. Construction of a complex (concave batter, berm and linear batter section) profile was completed in 2001 (Landloch, 2002). The slope was reprofiled from a single linear angle of repose slope (Landloch n.d.). The facility was constructed with an outer wall 35 m high (Figure 6). The WEPP model predicted that the rocky surface layer adopted would have low erosion potential, with mean annual erosion rates being <3.5tha^{-1} y^{-1}, an order of magnitude less than rates that have been observed by Landloch Pty Ltd to be associated with surfaces affected by rill and gully erosion.

Compared to the long term mean annual rainfall, the first six months of the slope's existence saw it exposed to more significant rain days (greater than the average) than would normally be encountered in two years. During an inspection, seven months after completion of the slope, even though the slope was subjected to several significant rainfall events, there was no evidence of erosion. This is consistent with WEPP model predictions. A small area of noticeably less rocky waste did show minor erosion, but this was discontinuous and consistent with the predicted patterns of erosion on a concave profile. Since 2001, Wiluna has experienced 10% wetter than average mean annual rainfall conditions. In this period two daily rain events have occurred with 10 year recurrence intervals, as well as two daily rain events with recurrence intervals of five years. The slope was reinspected in late 2010 (nine years after rehabilitation was completed) at which time it was determined that no further erosion was observed.

Figure 6 Reprofiled TSF C at Wiluna Gold Mine, 2001

5 Usefulness of erosion model results

5.1 Model calibration

The reliability of any model prediction is a function of both the suitability of model's internal equations to describe the processes being modelled, and the accuracy of the model's parameters. Use of inaccurate parameters will lead to inaccurate results. The evaluation data sourced to date indicate that the WEPP model can be:

- used to model erosion processes in a mining setting
- accurately parameterised.

The findings show that a landform design process underpinned by a suitably robust erosion model can significantly assist in planning for closure. It enables decisions to be made at an early stage of the mining process that inform landform construction, and improve outcomes (e.g. reduced erosional failure of slopes) during rehabilitation.

Landloch's methods of deriving the necessary parameters are also supported by these findings. Given that the accuracy of the input parameters can significantly change the model's predictions, the demonstrated accuracy of the model's predictions to date is an important finding.

5.2 Using model output for closure

During the early stages of mining (i.e. planning), erosion models are typically used to predict erosion for a given batter configuration. However, during closure activities, the model can be used to confirm that the landform performance is consistent with expectations. Given the significant variability that can occur in erosion from year to year, it is sometimes difficult to determine whether measured erosion in a given year is in accord with expectations. Use of an erosion model provides a means by which rainfall variability can be incorporated into considerations of annual erosion monitoring data.

If a slope predicted by the WEPP model to be stable in the long term is shown to erode in accordance with model predictions over a shorter period, it can be inferred that the landform will be stable in the long-term. That is, short term erosion and runoff data collected during monitoring campaigns can be used to validate the WEPP model predictions. The results can be used to confirm the erosional stability of the slope, and highlight areas of a landform that are being subjected to elevated erosive forces (e.g. by a failed berm discharging water from upslope areas to the batter.) This can lead to more effective remedial actions targeted at the cause of erosion.

5.3 Continual improvement of rehabilitation methods

Use of erosion monitoring data in conjunction with an erosion prediction model has led to continual improvements in rehabilitation methods, as this provides data necessary to make informed decisions. Two examples of how erosion models have improved rehabilitation methods are:

- informing the effectiveness and strategic placement of surface cover to increase erosion resistance
- demonstrating the influence of flow-concentrating features such as berms and rock drains on long term batter stability.

The WEPP model, in conjunction with the RUSLE, has been used to assess the potential benefits of placement of tree debris. Loch and Lowe (2008) report the erosion models being used both to assess the effect of different densities of tree debris placement (Figure 7), and also the use of tree debris strategically placed in isolated bands in the case where the resource is limited (Figure 8). Use of these models confirmed the need for additional works (placement of tree debris) to stabilise the slope, and also identified specific zones on which the limited resources could most effectively be used.

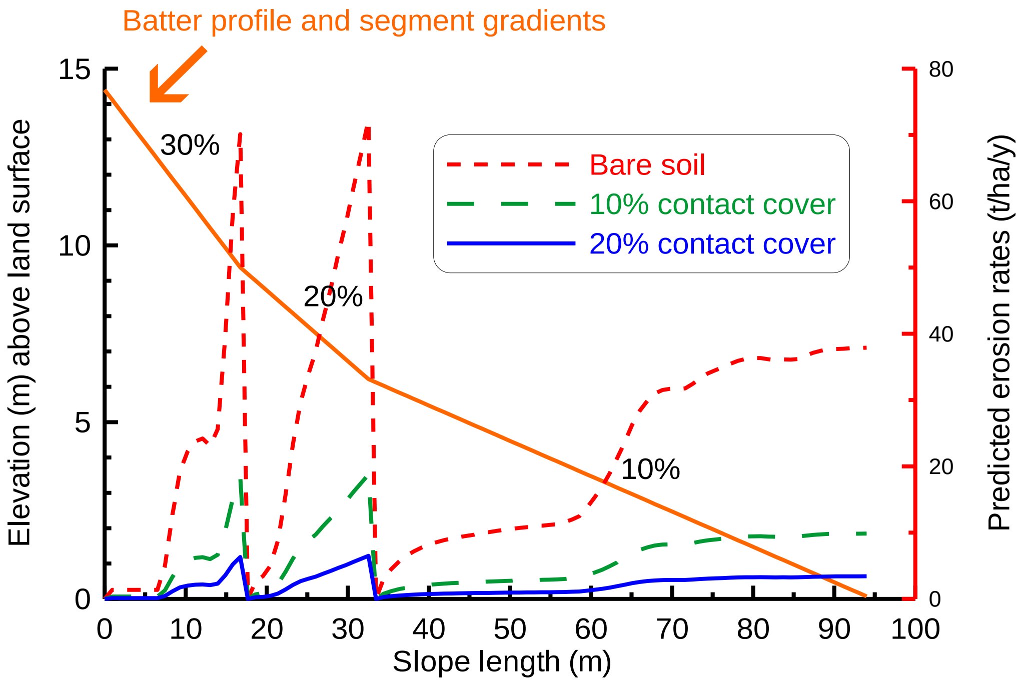

Figure 7 WEPP model output showing erosion patterns on a concave slope with different levels of tree debris (from Loch and Lowe, 2008)

The WEPP model along with other models such as the SIBERIA landform evolution model have been used to demonstrate the influence of flow concentration on surface stability (Howard and Roddy, 2012). An example of output from this model is given in Figure 9. Model output has been responsible for a move away by the mining industry from landform configurations that contain berms and rock drains. This has been of particular benefit to rehabilitation of landforms that contain dispersive and tunnel prone wastes (Vacher et al., 2004), as the presence of these structures renders landforms highly susceptible to both gully erosion and tunnel erosion (Howard et al., 2010).

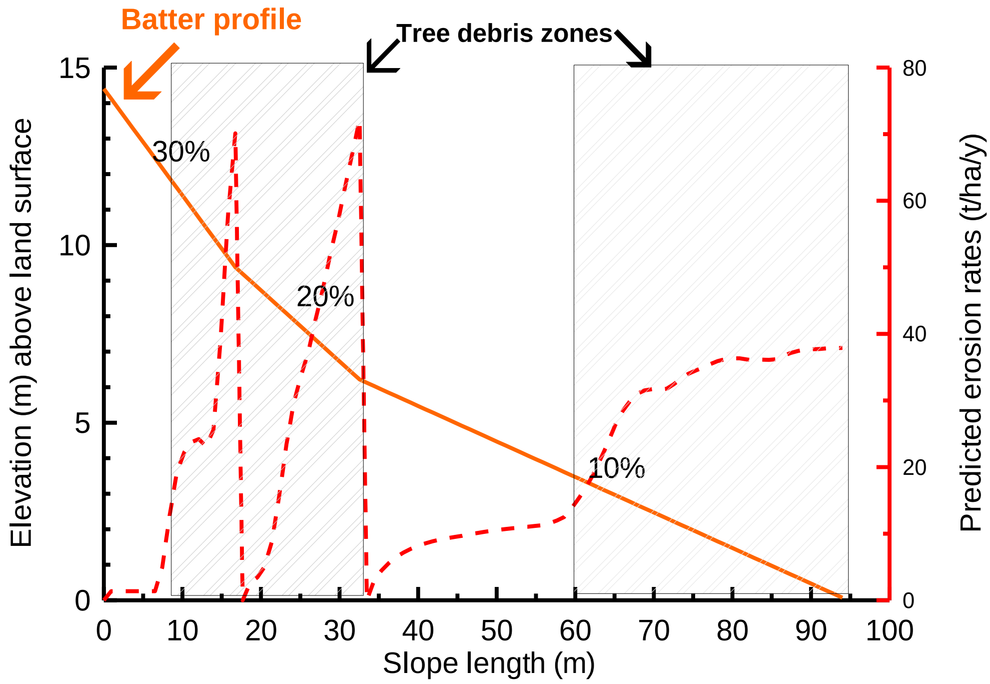

Figure 8 Zones of tree debris placement based on WEPP and RUSLE model output (from Loch and Lowe, 2008)

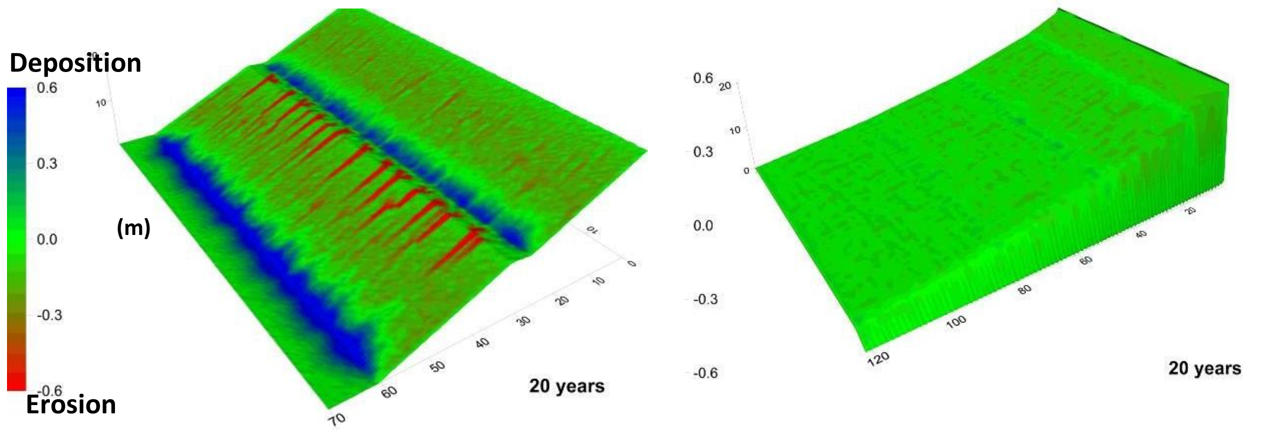

Figure 9 Erosion patterns predicted by the SIBERIA landform evolution model after 20 years for a batter of the same height and material: Gully erosion triggered by berm construction on the lower section of a waste dump batter (left); No gully erosion predicted where berms have not been installed

Conclusion

An evaluation of the WEPP model on 11 waste landform sites in Western Australia shows good agreement between WEPP-predicted and field-measured erosion rates. This is in accord with other evaluation studies that demonstrated that the WEPP model can adequately predict erosion provided high quality input parameters are available. The accuracy with which erosion has been predicted for these sites is evidence that the methods used by Landloch to parameterise the model produce well calibrated model results. Further validation of the model for use in mining is underway, and is anticipated to continue to improve outcomes for landform stability at closure.

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