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Improving landform design using analysis of high-resolution survey data from constructed linear and geomorphic landforms in New South Wales, Australia

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1 Abstract

Design of a stable post-mining landform typically goes through analysis at the design stage and then assessment using a landscape evolution model to demonstrate sustainability. The above methods generally rely on laboratory testing and computer models to quantify erosion risk. Real-world data is often scarce, and both time-consuming and costly to collect.

The authors have developed an innovative approach to analyse high-resolution lidar surveys using a flow model accelerated with graphics processing units to quantify the extent, depth and volume of erosion on a site using a single dataset.

The approach has been used since early 2023 on several sites in New South Wales, Australia. The outcomes provide useful data and highlight some of the opportunities, constraints and challenges for both traditional and geomorphic landforms.

We believe the learnings are useful for practitioners looking to apply both traditional and geomorphic design approaches.

Keywords: *landform design, geomorphic approach, monitoring, erosion rates*

1. Introduction

The authors have been involved with the geomorphic design of landforms primarily in the Hunter Valley in New South Wales (NSW), Australia, since 2012. The design methodologies used have ranged from analogues to combining analogue and static erosion risk assessments (Bugosh 2003; Hancock et al. 2020; Sawatsky & Beckstead 1996; Dressler & Waygood 2022). Almost all of the open cut mines in the Hunter Valley now use geomorphically designed landforms for rehabilitated mining overburden so there are numerous examples of these landforms in the area, with a range of average slopes and heights, and varying ages.

Although the authors have been involved in monitoring the performance of both geomorphic designs and the more traditional slopes, typically 1V:6H linear slopes with contour banks and drop structures, much of that information has been based on field observations and estimates made on site.

One of the major mining houses in the Hunter Valley (Glencore) was interested in innovative ways it could simplify its Rehabilitation Report Card and ensure that it was more objective. The company was already collecting lidar readings annually and was keen to understand if the quantification of rilling in terms of the length and depth could be automated. This data was previously collected by field inspections, which were time-consuming and also somewhat subjective: the areas in which rilling is more easily identified are those with poor vegetation and, while these tend to be where most of the problems exist, other rilling below more densely vegetated areas was being missed.

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This data is then categorised in terms of the length and depth of rilling, from which a decision can be made around the need for engineering interventions or simply ongoing monitoring.

Different options were considered for the quantification of rills, including machine learning and comparison of two surfaces (for example, an older and more recent survey). Both methods had advantages and disadvantages, including some relatively high costs for machine learning in particular and issues with settlement when comparing two surfaces.

A third option considered was to focus on water movement, with the advantage of then being able to distinguish between erosion due to water flow and other non-erosion-related changes to the surface such as machine tracks or settlement. The methodology is also able to quantify the depth and length of erosion from a single surface rather than requiring two surfaces. Based on favourable initial outcomes, this method was then adopted for the work.

2 Assessment methodology

Concentrated flow erosion features (such as rills and gullies) are significant components of erosion processes across a rehabilitated landform (Kelder et al. 2016; Loch 2010; Slingerland & Dressler 2022). Other processes include sheet and wind erosion, and material weathering (Flanagan & Nearing 1995; Howard & Roddy 2012; Howard 2018). This work focused purely on erosion rills and gullies, considered to be the main contributors to erosion rates on the sites at which we work.

As indicated previously, the approach adopted is to 'follow the water': that is, to simulate rainfall on to a surface and then model the behaviour of water flow across the surface. From this information it is possible to identify water flow conditions that are largely unique to such concentrated flow erosion features, i.e. narrow flow widths with reasonable flow depths, elevated velocities and high tractive stresses[†].

The Lisflood flow algorithm (Bates et al. 2010), implemented by the authors on graphics processing units for computational efficiency, is used to simulate water flow on a digital terrain model (DTM) generated from the survey (refer to Figure 1 for an example of the DTM). The premise behind the assessment methodology is that, provided sufficient depth of rainfall is simulated onto the surface, the rills will fill with water and runoff will then spill onto the adjacent wider surface. Once this happens the flow depth remains relatively constant due to the much wider general surface area compared to the size of the rills. Sufficient rainfall is required to fill all the rills with water, but not so excessive as to impact the assumption that the water depth at the rill location approximates the rill depth.

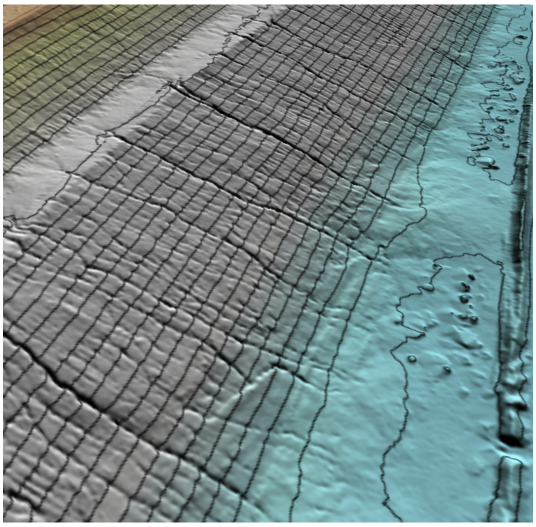

Figure 1 Digital terrain model (0.25 by 0.25 m) generated from a high-density lidar survey

[†] Tractive stress is a shear stress that describes the force applied to the surface by the flow of water

The scripting then assesses flow outputs to ensure that only rills are quantified. For example, deep water does not necessarily equate to an erosion rill but could be due to ponding of water or flow within contour banks. By assessing flow velocity and tractive stresses, these features can be automatically excluded.

However, on most landforms there will be features that have similar characteristics to a rill but that are not erosion related. Fortunately, these features are limited to primarily rock-armoured structures where flow depths are significant, and velocities and tractive stresses are high (refer to Witheridge [2009] for a discussion on the design of such structures). Currently these features are manually excluded from the outputs, although algorithms are being considered to automatically identify and exclude these features based on flow widths.

An example of the determined rill locations and depths, with modelled flow depth, velocity and tractive shear, is shown in Figure 2.

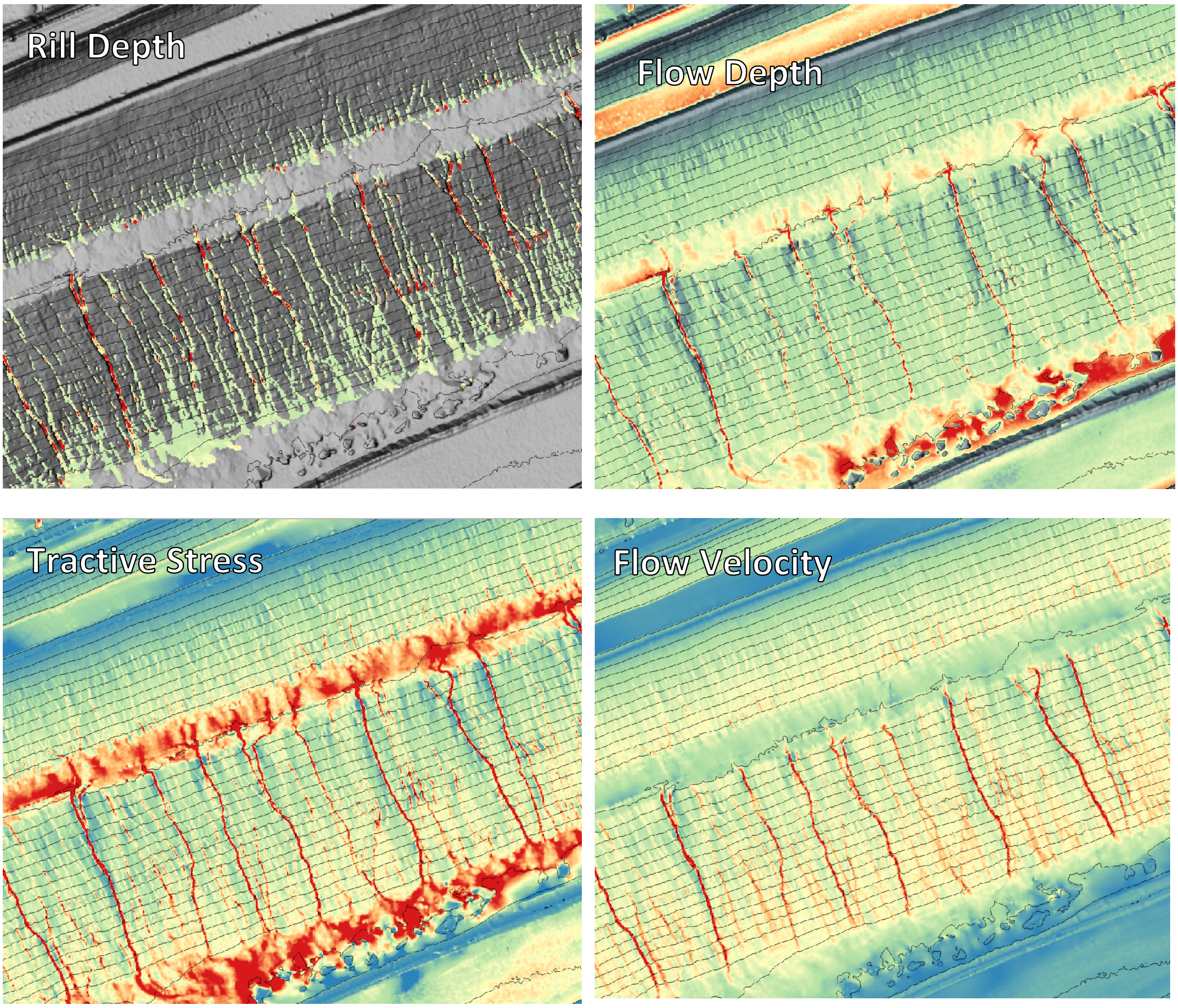

Figure 2 Example of the Lisflood model outputs. The flow depth, tractive shear and flow velocity are compared at each pixel and a thresholding operation is undertaken to determine whether a point should be classified as a rill

The assessment criteria shown in Table 1 are then used to determine intervention thresholds, although these can vary for different sites and/or clients. While depth is computed from flow depth at a point in the rill, the rill length is computed within the scripting by tracking iteratively uphill within the flow data to locate the highest point within that rill and then following the flow to the bottom of the rill.

Table 1 Typical classification

Description	Classification
Minor sheet erosion or rills < 100 mm depth Rills 100 < 300 mm and > a specific length, often taken as 10 m	Areas that are performing well and only ongoing monitoring is required
Gullies 300 < 500 mm and > the same length as above	Targeted monitoring required
Gullies 500 < 1 m depth and > the same length as above	Areas of concern to be assessed by a qualified person
Gullies > 1 and > the same length as above	Areas of concern to be assessed by a qualified person with a prioritised action plan

2.1 Note on accuracy

As with any modelling work there will be assumptions in the assessment that impact the accuracy of the outcomes. The following limitations are relevant to the outcomes:

- Using 20 points/m^2 will not provide exact cross-sections for all rills.
    - This impact is exacerbated once the data is adjusted to a regular grid. However, the data sets become extremely large as the number of points and grid sizes are reduced, and 20 points/m^2 appeared to give well-defined rills in the surface when inspected visually. To estimate rill cross-sections, the initial work used published data to determine the profile from the known depth. This work was supported by some ad hoc checks on the cross-sections where denser survey data was available.
- The size of grid used in the assessment will also impact the outcomes.
    - We evaluated the impact of grid size from a grid of 0.25 m blocks down to 0.05 m blocks. We found that the difference in accuracy was around 10 to 15 per cent. For the purposes of this work, this level of accuracy with the coarser blocks was considered acceptable given the significant additional time and computing power required to process much larger files.
    - This does not preclude using smaller grids and higher-density surveys for specific applications, but these would likely need to be on relatively small areas.

The combination of the above errors and possible survey errors means that the indicated erosion rates are not absolute and, as more data is collected, the extent of the applicable error bar will be refined. However, the trends observed are valid and, in the authors' view, this is more critical in demonstrating long-term stability than the exact erosion rate achieved.

It is important to note that while the initial outcomes from modelling are then subject to field validation, specific areas of concern or interest can now be targeted rather than wandering over the site. This field work also allows an assessment to be made of which rills are active or look likely to have the potential to become active in the future.

3 Key outcomes

Even without undertaking quantification of the rill depths and lengths, the high-density DTMs provide a high level of detail of the sites that can be useful. Examples of the level of detail evident in the images is shown in Section 3.1, together with outputs from the analyses.

3.1 Outputs

Typical outputs of the erosion assessment are shown below. These outputs can be used to inform maintenance plans, alter future design parameters and demonstrate the stability of the site. The outputs presented are the initial rill tracking with flow depths (Figure 3), and classification of the data into grids to allow easy identification of problem areas, based on the maximum rating within a particular grid (Figure 4). Note that the classification blocks are coarser (shown here at 10 by 10 m).

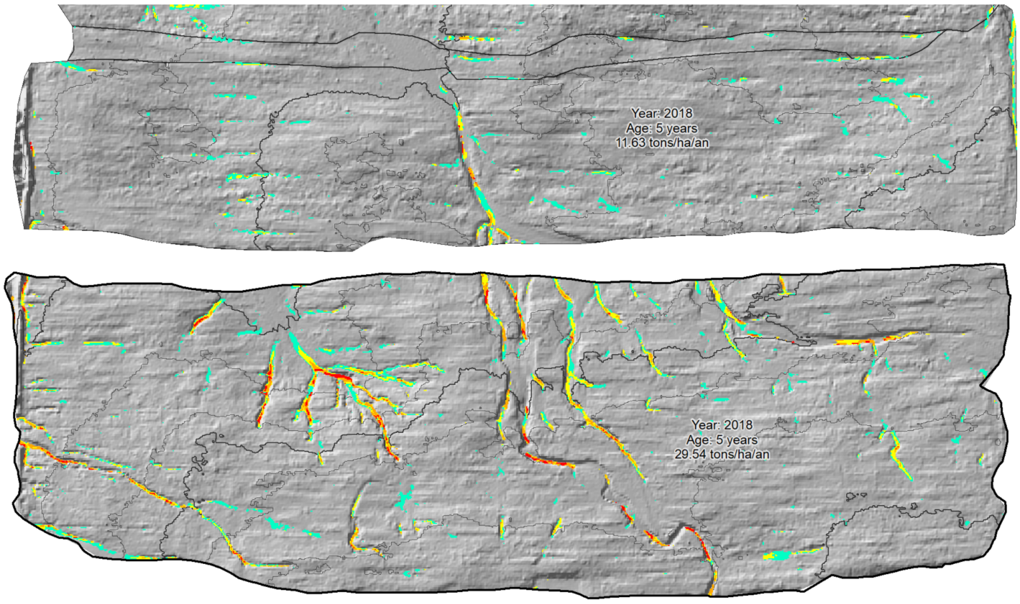

Figure 1 Typical output of the assessment, with warmer colours indicating increasing erosion depth

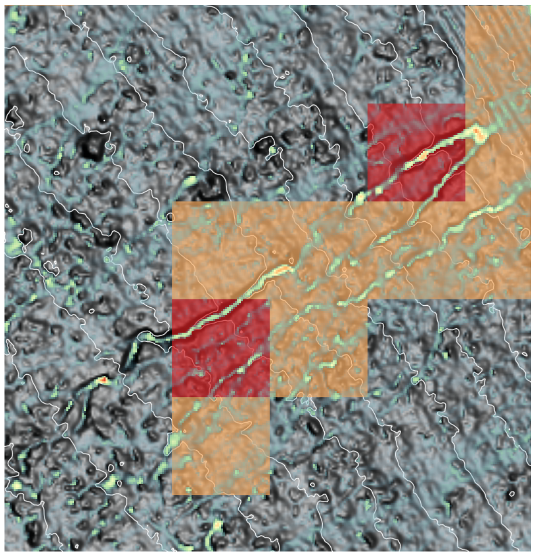

Figure 4 Typical classification output

As indicated previously, knowledge of the depth and length of rilling makes it possible, using an estimated cross-section, to gauge the volume of material generated by the rill. If the date of rehabilitation is known, the average erosion rate since the last survey can then be quantified.

It is important to note that this erosion rate is not the erosion rate at a particular year but rather the average erosion rate since the date of rehabilitation or since the last assessment, if one exists. Other data, such as the area of rilling and average volume of material lost, can also be determined, which can be useful for slope stability assessments.

An example of computed average erosion rates for a collection of sites is shown in Figure 5, with a significant reduction in average erosion rates with time as vegetation is established and the soil profile becomes more mature. This trend is typical of what we are seeing on most sites.

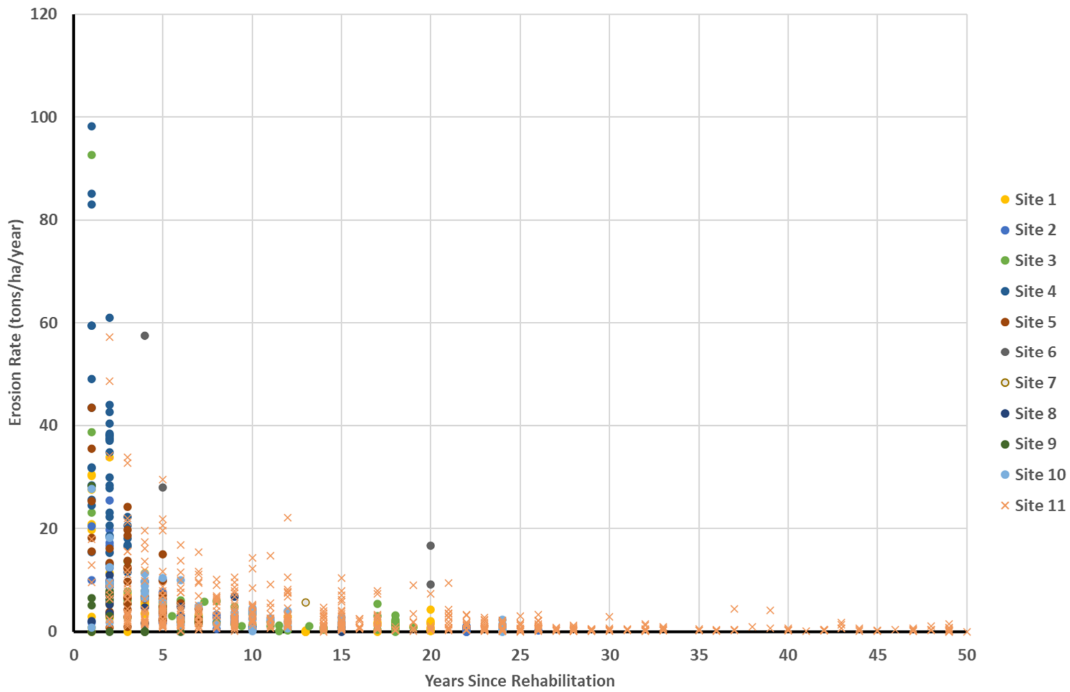

Figure 5 Typical erosion rate output

3.2 Key learnings

Several learnings have come out of this work; some self-evident but others not.

3.2.1 Erosion rates

There seems to be a remarkable consistency in the erosion rate trends observed over the period assessed. Although site 11 in Figure 5 has 50 years of data, most of our work to date has been on landforms with up to 26 years of data (sites 1 to 10 in Figure 5).

As discussed previously, the trends are very favourable. Erosion rates appear to halve from their initial construction period rates within three years, and by year six, most sites are trending to levels that are within or close to target erosion rates reported in literature as potentially acceptable: typically less than 10 t/ha/year and in many instances under 5 t/ha/year. Even with allowance for error, the computed erosion rates are low.

The presence of outliers also indicates that parts of some sites are exhibiting above-average erosion rates, and these can then be flagged for improvement early on in the landform management process. These outliers are further discussed below.

It should be noted that both the traditional and geomorphic landforms in the Hunter Valley have been designed quite conservatively to limit the risk of rilling prior to vegetation being established. The conservative spacing used historically between contour banks on most sites is close to the spacing required to limit erosion, even without vegetation. The issues observed on most traditional landforms do not typically relate to erosion on the overland flow but rather to failure of the contour banks or associated drop structures.

The geomorphic landforms have been designed slightly less conservatively in terms of erosion risk for overland flow compared to traditional designs but, with experience over time, the target values have been adjusted to limit rilling prior to vegetation becoming established. These surfaces are then conservatively designed once vegetation has become established. Nevertheless, managing construction risk for geomorphic landforms remains one area of risk that is subject to ongoing optimisation and adjustment for different sites on varying soils and ranging climatic conditions.

From a design perspective the key learning from erosion rates is that there is an appropriate level of risk to be incorporated into the design, specific to each site and allowing for monitoring of landform performance. For sites where vegetation cover will be significant, the construction period remains the key period of risk to be managed.

3.2.2 Observations of the nature and location of rilling

The location and nature of observed rilling will be discussed in more detail, but an example is given in Figure 6.

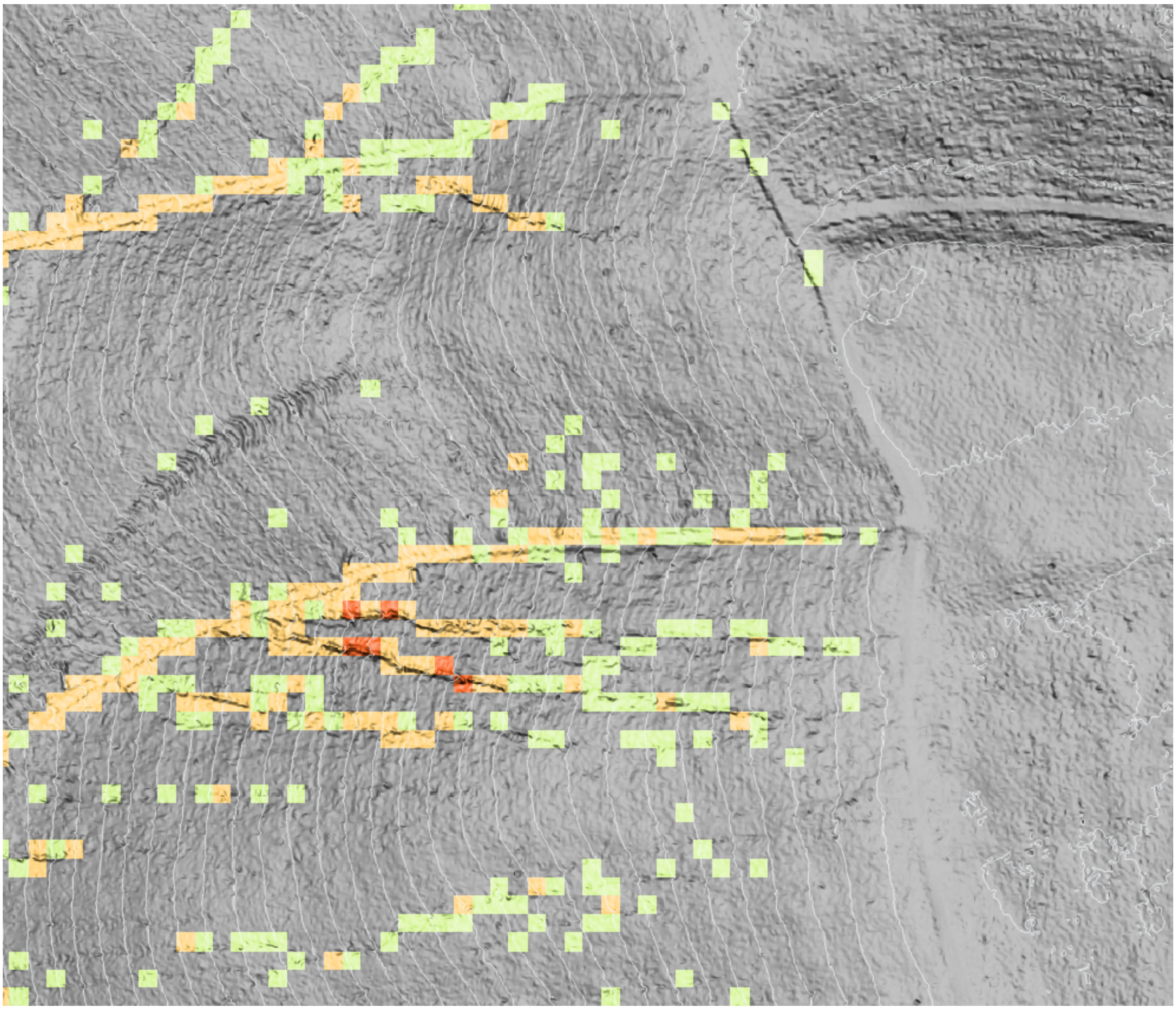

Figure 6 Example of observed rilling

To understand the learnings from observed erosion the cause of the erosion needs to be understood. While there can often be an overlap in these causes, at least one of the following issues is generally present:

- construction-related issues such as poor water management
- optimistic soil erodibility values for a particular soil in a particular climatic condition
- extreme weather conditions
- designs that could be improved.

3.2.2.1 Construction-related impacts

Rilling observed towards the top of a landform (refer to Figure 6) is often related to construction issues; a catchment area being mostly too small to cause significant rilling.

These issues are often caused by overspill of water from temporary terraces above rehabilitated areas, the impact of vehicle traffic up a slope forming a preferential flow path, or the delayed installation of rock armouring where required in drainage lines or drop structures.

As discussed in Section 3.2.2.2, deep ripping using a dozer and ripper attachment is generally employed to increase infiltration and limit runoff as part of the rehabilitation process. However, sometimes the rip lines are irregularly spaced or don't run on, or close to, a contour, resulting in flow concentrations in unexpected areas. Tree mounds are also sometimes used. This method of ripping forms a bund with a deep rip under it that ensures water accumulates in the area where trees are to be planted, but these need to be on, or close to, a contour line.

Despite the significance of rilling during the construction phase it should also be noted that many of the rills formed during the construction phase are stabilised once vegetation is established. A key part of the rehabilitation performance process is not just to identify rilling but also to assess which rills have been stabilised through vegetation establishment and which have not.

3.2.2.2 Soil erodibility values

Climatic conditions in the Hunter Valley can be challenging. The annual rainfall of around 700 mm facilitates vegetation establishment but variable and hot dry summers, with temperatures approaching 40°C, are not uncommon. The rainfall is also inconsistent, with periods of drought lasting several years.

Although good vegetation cover is generally established within two to three months, in arid periods this could take two to three years due to tough climatic conditions.

The design methodology that WSP employs utilises soil erodibility data, obtained from flume testing and associated analysis using the water erosion prediction project (WEPP) method or by erosion quantification on an existing rehabilitation that has been exposed to several years of rainfall. The WEPP analysis provides erodibility data of both the bare soils and the vegetated surface. Geomorphic designs undertaken by WSP in the Hunter Valley use an erosion risk that is not based on the final vegetated surface or the bare soil but on a value somewhere in between. This provides some safety margin to limit rilling during adverse climatic conditions without being excessively conservative.

The erodibility of soils remains a challenge, however, particularly during pre-vegetation. For example, even though chemical stabilisation of dispersive soils through the addition of gypsum is widely practised, the beneficial impact of stabilisation can take many months.

The adequacy of the target values can be considered by evaluating rills that occur further down the slope (refer Figure 6). Excessive rilling typically suggests that the target may be too high, provided extreme weather conditions (refer Section 3.2.2.3) and construction issues can be excluded.

3.2.2.3 Extreme weather conditions

Despite the best planning, there are times where a newly shaped and topsoiled surface will be subject to intense rainfall, with or without deep ripping or alternative surface roughness. These rills can be spread across the surface but are typically more pronounced further down the slope.

In theory, this risk can be managed by a more conservative design targeting a lower erosion risk.

There is a trade-off, however, between a conservative design and the cost; be it the cost of additional drains in a geomorphic surface or more robust/closely spaced contour banks. The methodology set out here is hugely useful for this period of review and updated analysis. It is normally not cost effective to design the surface to be able to withstand very extreme events without significant vegetation cover.

3.2.2.4 *Designs that could be improved*

For geomorphic designs, the better performing ones tend to have surfaces that are well rounded and limit the length of overland flows so that water reaches drainage lines before rill formation becomes excessive. Sites with an appropriate level of curvature perform better than those that have more planar components, and the drainage density is also a key factor. It is difficult to quantify the degree of curvature required but it seems evident on landforms where flows are dispersing that rills are less likely to result in significant flow concentration compared to areas that are either linear or only slightly dispersing.

For linear designs, the better performing surfaces have contour banks bedded well into the surface and drains that are robust in width and height. Contour banks seem to be more vulnerable to piping failures as the average slope steepness increases, with some significant failures observed on a few sites with slopes steeper than around 14°.

As may be expected, the 'failure' modes or rilling observed for linear and geomorphic designs are very different.

For linear designs, failures in the short term seem to be primarily associated with piping failures due to dispersive soils and inadequate contour bank design or maintenance. These can be progressive, and one point of failure generally progresses down the slope. The most significant of these rills are due to piping failures, which can result from something as simple as vegetation overgrowth causing ponding. While there are longer-term issues for contour banks associated with sediment accumulation and possible overtopping, this failure mode has been observed mostly on sites with very narrow and shallow contour banks due to the relatively limited duration of exposure.

For geomorphic landforms, failures tend to be back towards the drainage lines and are then managed there, so the extent of failure is more confined except on more linear surfaces.

A last point to note about failure modes is that a downward trend in erosion rates will adjust if an event occurs to trigger an incremental change in the landform erosion. We have observed this in the data some of these events, primarily contour bank failure for traditional designs.

The ability of geomorphic designs to be 'fail-safe' seems to be a major advantage in the longer term: that is, assuming the rock-armoured components of the surface are stable, the risk of an incremental change in erosion rates appears unlikely.

Note that the risk of failure of the rock-armoured components applies to both traditional and geomorphic designs, and the precautionary approach towards this element of the landform design is detailed elsewhere (Dressler & Waygood 2022).

4 Conclusion

Collection of real-world data is a hugely important step in validating the appropriateness of models and design approaches. Being able to quantify erosion rates, areas of erosion, and the extent and depth of erosion is extremely useful.

The outcomes have generally been better than expected: that is, erosion rates seem to be trending downwards on almost all sites. While there is an error margin to be applied to the absolute rate, the trends seem to be approaching targets set in literature as reasonable for rehabilitated landforms in the areas assessed.

The above notwithstanding, construction-related impacts that could result in a portion of the landform being outside of the desired erosion rate trajectory are evident on some sites, and these are mostly easily addressed.

The issue of an acceptable erosion risk used in the design process is, in our view, subject to ongoing refinement and assessment on specific sites, with data used to evaluate the performance of the landform through periods of climatic adversity, and consideration of both the variation in soils and different rehabilitation strategies. We see the process of data collection set out here as being an extremely useful tool in this process.

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