

Understanding the limits of alluvial analogues: lessons from geomorphological design of mine rehabilitation in New South Wales, Australia

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Abstract

A geomorphological approach to landform design aims to pattern constructed landforms in erodible materials on natural landforms. These natural landforms represent a mature geomorphic condition subject to a slow rate of evolution. Most commonly, stable alluvial landforms in the local environment are utilised as analogues. Unfortunately, few landforms constructed in mining overburden in New South Wales, Australia, have an overall geometry that allows for alluvial analogues to be directly applied; that is, the post mining landforms are frequently too steep.

To address this challenge, approaches used internationally range from very sinuous drainage lines to flatten gradients, through to wide grassed drains to reduce velocities, and the use of rock armouring in drainage lines. Each of these approaches has some challenges. Overly sinuous designs move away from a dendritic drainage layout and are overly complex to construct. They are also vulnerable to piping failures. Wide grassed drains can develop preferential flow paths and can also impact unfavourably on the overall drainage density. Rock armouring is not generally favoured by geomorphologists since armouring represents a rigid conveyance system without self-healing capabilities.

The strategy adopted by the authors is to design drains using a vegetated rock matrix approach. Effectively, a dendritic drainage layout is used at a desired drainage density, and the drain widths and/or longitudinal slopes adjusted to ensure that the drains have velocities below 3 m/s even for the design event (typically the 1:100-year event). These drains are wider and shallower than a typically optimised trapezoidal drain and, for frequent flood events, the rock is primarily required for the roughness it adds to the surface.

With relatively low design velocities, sediment accumulates within the rock voids and revegetation of this material significantly increases the rock stability. The embedded rock and revegetated matrix are then able to withstand extreme flood events well above the original design event. This larger flood event is more in line with that expected for the required design life of these surfaces.

It is noted that, because the rock size required is proportional to the velocities, increasing the drain perimeter by designing a flatter, wider drain does not necessarily increase the cost of the lining because smaller rock sizes result in reduced thicknesses of the rock lining.

Keywords: *landform design, geomorphic approach, alluvial analogues, rock armouring*

1 Introduction

A few decades ago, constructed landforms had to utilise linear slopes for ease of setting out; however, with the advent of GPS-guided construction equipment, surfaces can now be designed in three dimensions and then uploaded for construction.

Consequently, the 'conventional approach' to land restoration using constant gradients, terraces and contour banks has evolved in many instances. Non-linear designs could include concave slopes based on material's erodibility analyses (Howard & Roddy 2012) through to more complex natural landforms with examples in

the United States (Bugosh 2003), Canada (Sawatsky & Beckstead 1996), Spain (Martin Duque et al. 2019, 2021) and Australia (Kelder et al. 2016).

Increasingly, we are also seeing the use of landscape evolution models (LEMs) (Hancock et al. 2020) to both guide designs and to demonstrate 'safe and stable' post-closure, with long modelling periods of up to 1,000 years being considered in New South Wales (NSW), Australia.

Given the increasing trend towards geomorphic designs compared to 20 years ago, it might be expected that there would be a trend towards similar designs making allowance for differences due to the climatic and soils/revegetation differences. However, this is not the case, and there are fundamental differences in approaches used by various practitioners. Some of the limitations of the different approaches are discussed below.

Importantly, the discussion in this paper focuses on water-shedding surfaces that are expected to sustain vegetation in the long term.

2 Design options

The two key design approaches are those that incorporate drainage lines into the surface, and those that do not. The use of drainage lines commonly seeks to achieve a particular drainage density on the landform, this being the number of drainage lines per unit area.

2.1 Designs without drainage density

Since flow concentration is known to be a key cause of erosion, intuitively, by preventing concentrated flow, we can potentially reduce the risk or associated consequences of erosion. The methodology used is generally to use a two-dimensional (2D) analysis method such as the Revised Universal Soil Loss Equation or the Water Erosion Prediction Project to generate an appropriate concave slope for a particular material (Loch 2010; Howard 2018).

The main challenge for these designs, in our view, is implementing what is effectively a 2D design into a three-dimensional (3D) space. Typically, the design will allow for the 3D nature of the construction by assuming a rill spacing, often of the order of 3 m to 5 m. For low slopes, such as in the range of 20 m to 30 m in height, with normal construction tolerances, this rill spacing can be relatively easily achieved with flow maintained as sheet flow.

However, as the size of the landform increases and the footprint becomes more complex, flow concentration becomes more likely, potentially resulting in the formation of drainage lines with significant catchment areas. This can be due to normal construction tolerances (Slingerland & Dressler 2022), the presence of internal and external corners, or even the impacts of fauna and flora.

These designs seem to be best suited to relatively low landforms that are outwardly rounded rather than larger landforms with complex footprints.

2.2 Designs with drainage density

A geomorphological approach to landform design incorporates the use of drainage density based on observations of natural landforms, typically using stable alluvial analogues in the local environment. Alluvial analogues are formed in weathered and transported material deposited by river systems, and the absence of solid rock makes them appropriate to landforms designed for mined overburden.

There are some key limitations to applying alluvial analogues. For example, natural analogues are generally already vegetated, whereas constructed landforms need to allow for the transition from bare soil to vegetated surface. However, the greatest limitation is that average slopes of alluvial analogues are relatively flat, with average slopes in the Hunter Valley, NSW, of around 5% or 6%.

The drainage plan views of alluvial analogues also tend to be dendritic, similar to Category A, B or C in the Rosgen (1996) classification system (Figure 1). While this is not a limitation, it is worth noting that the drainage lines have a moderate to low sinuosity and a moderate to low width/depth ratio. Although Category A channels can be also found at steeper gradients in weathered non-transported materials, these are not generally applied as a relevant analogue to mined overburden.

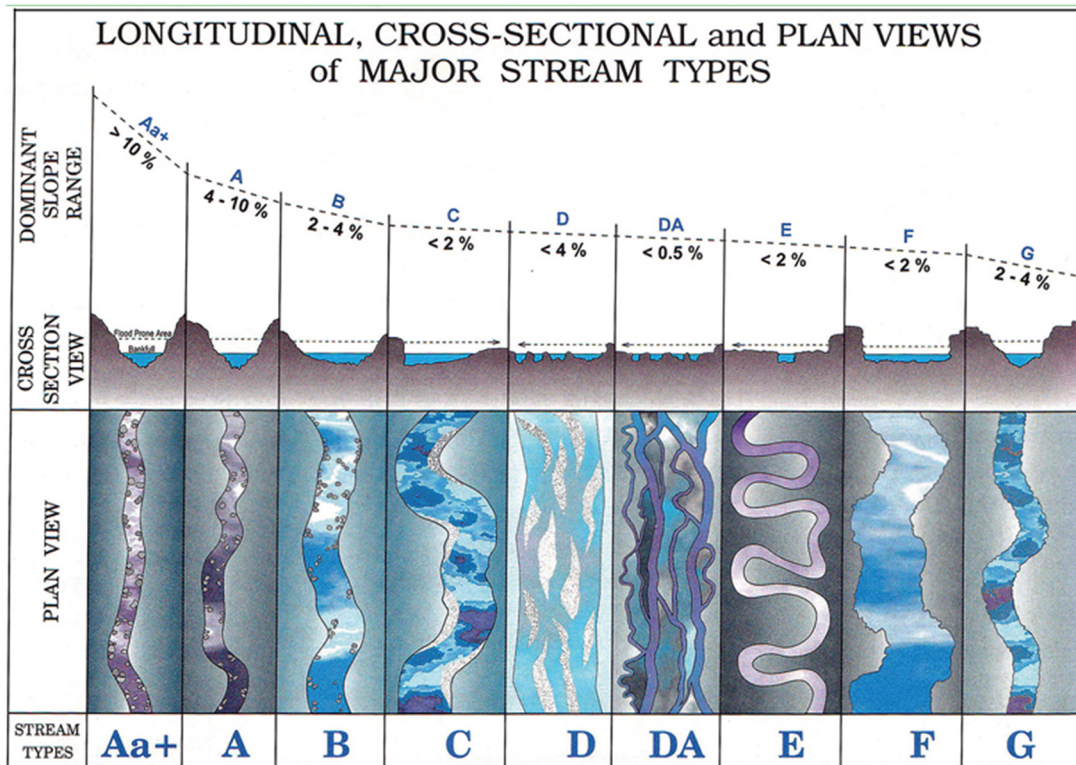


Figure 1 Classification of stream types (Rosgen 1996)

Compared to the natural slopes, most mining sites in NSW were originally conceived as having flat upper surfaces and 17% side slopes incorporating contour banks, and final levels and landform footprints have been based on these. These are therefore much steeper than the alluvial analogues – an example of this for Mt Pleasant is shown in Figure 2.

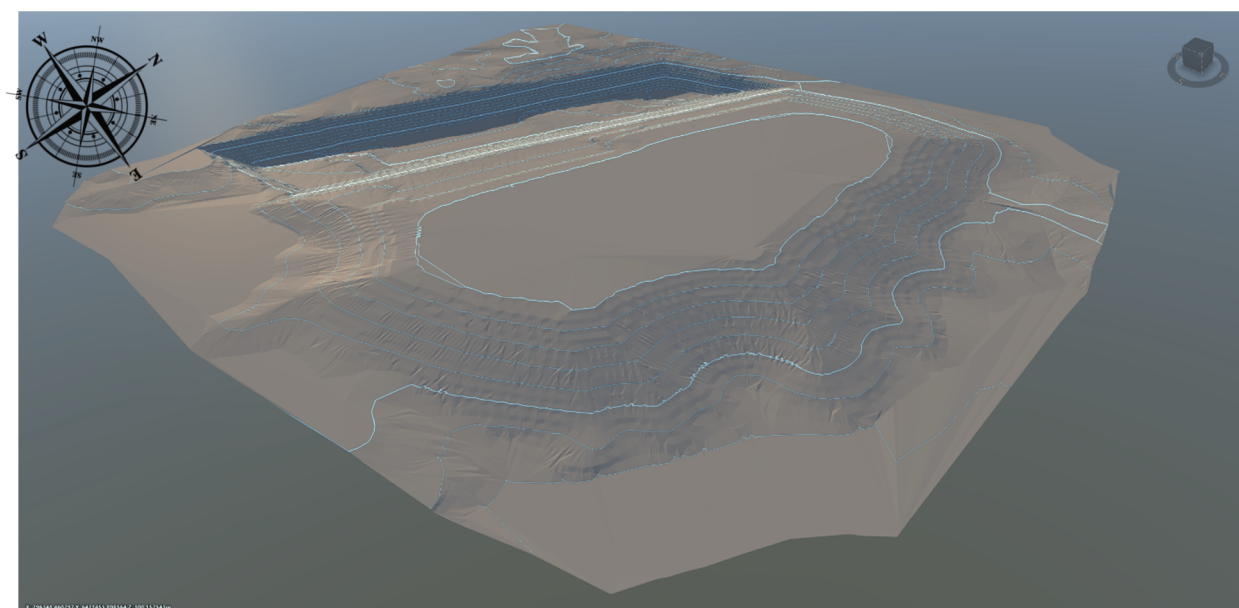


Figure 2 Mt Pleasant original landform design

Using the analogue methodology on a site like Mt Pleasant will result in the upper surface being drained using relatively flat gradients. This can be achieved without compromising on the overall volumes; however, the designer is then left with a significant extent of side slopes steeper than the alluvial analogues. This part of the landform requires a different strategy.

Possible methods to address landforms steeper than alluvial analogues are discussed below. Importantly, in our view, any surfaces steeper than analogues will require assessment using an LEM or similar methodology, and we tend to use erosional risk assessments for all our landforms regardless of the analogue being used.

2.2.1 *Increased sinuosity to flatten gradients*

One approach is to increase the sinuosity of the main drainage lines, effectively mimicking the Rosgen stream Type E (Loch 2010). With a very sinuous design, the overall gradient of the main drainage line is reduced to close to the alluvial analogues. There are several problems with this approach in our view, including:

- These surfaces become highly convoluted, and while the longitudinal slope of the main drain is flattened, the overall average gradients are not. It is not uncommon to have a significant proportion of the surface steeper than 33%, which is the maximum slope limit we use for safety in construction.
- Moving water sideways across a slope is inherently risky for landforms that will settle, particularly if these landforms contain dispersive material, with an associated risk of piping failure.
- Construction of convoluted surfaces is challenging, with extensive sideways dozing likely.
- The designs do not blend well visually with our typical Hunter Valley landforms.

2.2.2 *Using wide drainage lines to reduce velocities*

Velocity is proportional to flow width and wider drains can reduce velocities such that stabilisation is possible using vegetation only. However, there are practical constraints, with the risk of preferential flow paths and subsequent erosion.

We have had success with wide drainage lines, but typically only for landforms that are slightly steeper than alluvial analogues, incorporating temporary erosion protection and ensuring the widths are not excessively wide.

2.2.3 *Rock armouring – the use of vegetated rock matrices*

From a geomorphic perspective, incorporating rock armouring moves away from the concept of dynamic movement within a landform, with erosion and deposition and migration of creek lines. As a result, rock armouring is not favoured, as the drains are without self-healing capabilities compared to rocky drains seen in the natural environment.

Consequently, Sawatsky & Beersing (2014) have suggested that, if the consequences of creek migration are significant, deep armouring or sacrificial sections of rock should be considered to mimic the self-healing capability of natural drainage systems, that is, allowing some erosion but still constraining the extent of erosion and deposition.

While we are supportive of the concept of dynamic design allowing for erosion and deposition, we would argue that the nature of the landform and the long-term erosional stability requirements of the regulator in most instances preclude allowing significant erosion, deposition and/or migration of drainage lines within a rehabilitated mine overburden surface. The capacity for self-healing within the rehabilitated surface is also quite limited, given that we typically have a thin layer of soil overlying a large body of weathered rock.

Within a geomorphic landform that has dendritic drainage, the drainage lines are well embedded in the surface, and it is possible to design rock lining to form natural-looking rocky creek lines. However, there is a challenge with the required life span – if the drain is to be designed to last for 1,000 years, then the design event needs to be appropriately extreme. However, a very extreme design flood event will result in

excessively large rock sizes when compared to the more frequent flood events, and often the rock size becomes impractical in the context of the width of the drainage lines.

A possible strategy to address this dilemma is the use of vegetated rock matrices for the drainage lines. The design approach can be summarised as follows:

- Drains are sized to have a target design velocity at or lower than 3 m/s. A graph of flows/metre width versus slope is shown in Figure 3, which allows appropriate drain widths and slopes to be targeted. Sinuosity would typically be around 1.2.
- These drains are designed so that the rock is stable for a suitable extreme event such as the 1:100-year event. This generally results in a shallow flow depth and wider profile, often with widths in the range of 3 m to 15 m.
- Sediment accumulation within the rock matrix and subsequent revegetation occurs during the more frequent rainfall events. This process beds the rock and associated soil matrix – we have observed how rock that was previously loose and easy to pick up can no longer be removed by hand without a spade or crowbar.

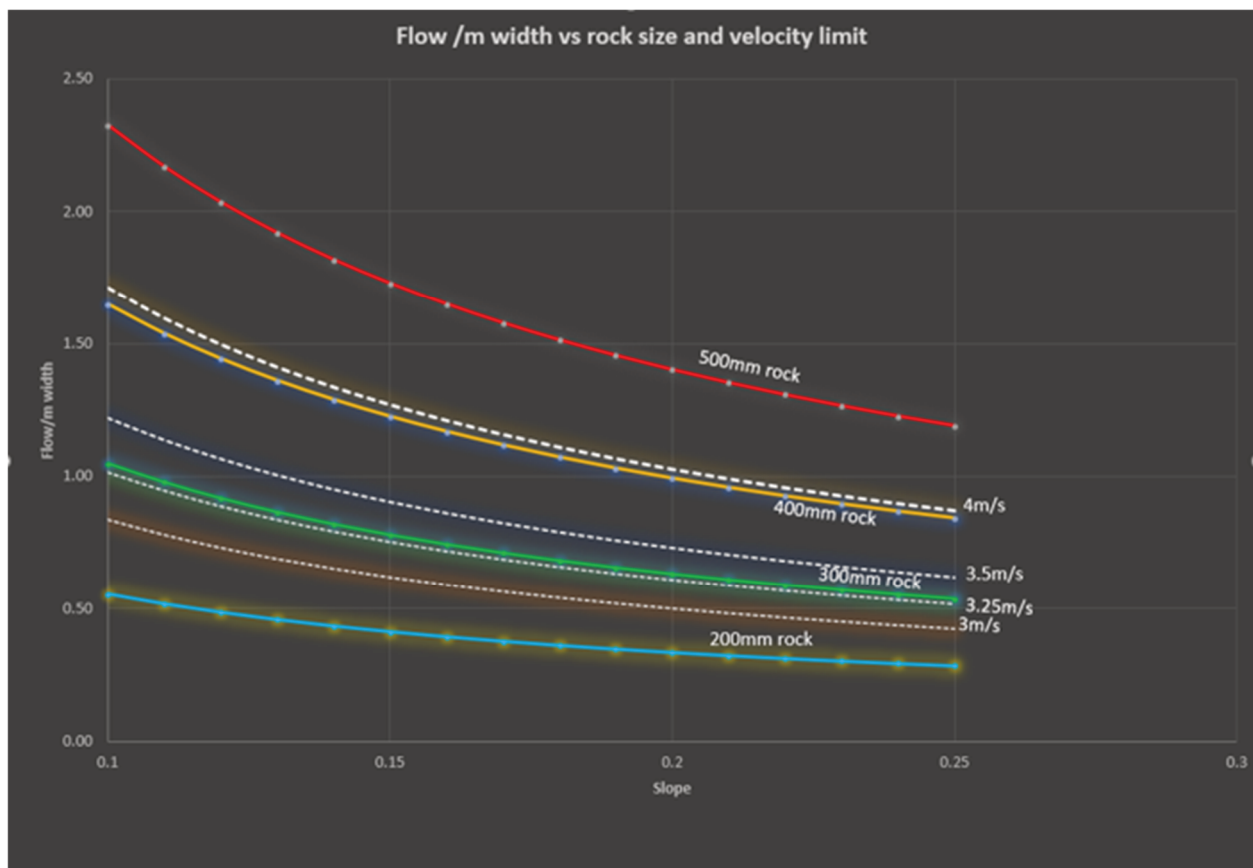


Figure 3 Rock size and velocity trends (equations from Witheridge (2009) and the Manning's equation)

Note: Figure 3 is specific to a particular rock, and the graph will vary for different rock types, densities, shapes, and estimated roughness.

Engineers are familiar with optimising conveyance of drainage lines, tending towards a trapezoidal profile using an inscribed circle, and these wider shallow drains would be considered hydraulically inefficient. However, the correlation between flow velocity and rock size means that lower flow velocities require a smaller rock size and, in turn, a thinner layer of rock, so that the drainage line cost is not proportional to the wetted perimeter. In our experience, smaller rock with a D_{50} of around 300 mm is also easier to place to line and level to have an even flow depth. We have also noted that within a geomorphic landform, flow depths

and velocities do not increase dramatically during very extreme flood events, as the side gradients tend to be relatively gentle. Examples of drains designed incorporating revegetation and sediment accumulation are shown in Figure 4.



Figure 4 Rock drains incorporating revegetation and sediment accumulation

Using this approach results in several key outcomes. Dendritic drainage patterns are maintained, and the final surface will be similar in appearance to many of the natural surfaces in the general area. Also, sideways flow on the surface is largely limited to the overland flow, and the simpler design is easier to construct than more complex or highly sinuous designs.

The geomorphological design for Mt Pleasant using the above approach is shown in Figure 5. Construction of this landform has been progressing since 2018.

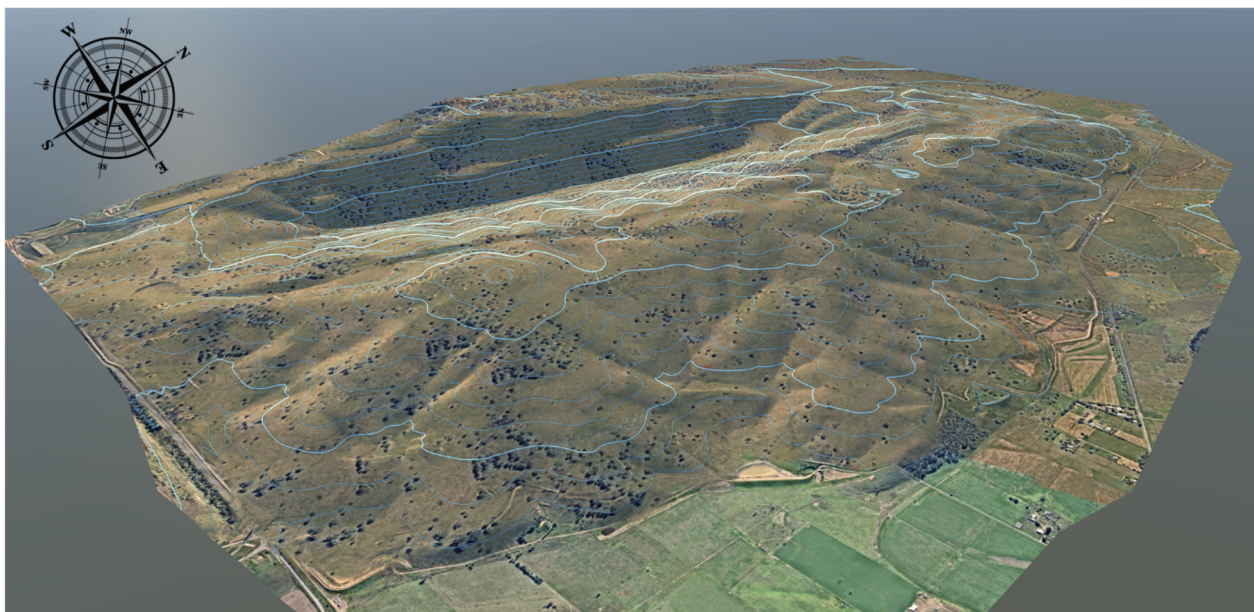


Figure 5 Mt Pleasant geomorphological design

3 Conclusion

To be consistent with the use of analogues, strategies for geomorphic designs should maximise the use of alluvial analogues as far as is practical, especially for the larger catchments such as the flat upper surfaces of the traditional designs.

For landforms with average slopes slightly steeper than those alluvial analogues, wide vegetated drains can be considered, provided the width does not become excessive.

However, for steeper average side slopes, our preference is to use dendritic drainage with a ‘normal’ sinuosity of around 1.2 or similar, and a vegetated rock matrix in the drainage lines. These designs use appropriately low velocities and small rock size to allow sediment accumulation within the rock matrix and revegetation of the infill material.

While the rock alone can withstand an extreme event of around the 1:100-year event, once vegetated, the vegetated rock matrix is inherently far more stable, potentially able to withstand significantly more extreme rainfall events. This long-term stability is enhanced by the wide drains within a geomorphic landform where flow depths and velocities do not increase dramatically during very extreme flood events.

While the above approach has been supported by observations on site, trials are being planned to quantify the observed benefits associated with bedding in of the rock and associated revegetation of the drainage lines.

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