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Mining rehabilitation – Using geomorphology to engineer ecologically sustainable landscapes for highly disturbed lands

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ABSTRACT

Mining is essential to the human economy and has been conducted for millennia. In the past ~60 years, the scale of disturbance created by mining has grown larger in response to economic demands and technology capacity. However the scale of disturbance from mining is dwarfed by that of urban expansion and agriculture. Nevertheless, it is well recognised that mine sites have radically disturbed abiotic and biotic system components that, post-mining need to restore new land uses and ecosystem goods and services. In many cases, such aims demand a geomorphic integration with the surrounding undisturbed landscape. Erosional stability based on geomorphic principles is the first and most important part of the process. Without erosional stability, vegetation will be difficult to establish and maintain and soil and nutrients will be lost from the site. In this review we outline this process and methods by which a geomorphic and integrative landscape can be established. We also examine the issue of establishing a self-sustaining landscape that is similar to that of the prior undisturbed landscape. Here we argue that this is not possible in almost all situations, however the development of a new and ecologically successful, albeit different landscape is. The community needs to accept that mining, like agriculture, is essential to the modern economy and that a past landscape cannot be replaced with the same, but a new, functional and productive one can be developed. However, the ability to do this and ensure long-term ecological sustainability is questionable for many sites and considerable effort needs to be made to develop the technology to ensure that this will occur. We outline a way forward, based on geomorphic design and modelling.

1. Introduction

Mining provides considerable economic and social benefit to the global human population. However, mining is an intensely transformative activity where the earth is removed to extract or exploit a resource (U.S. Dept. of Interior, 1971; Young, 1992; Mossa and James, 2013). Here we focus on open cut mining where the earth's surface is removed to expose the resource. Open cut mining 'opens up' the landscape to access and extract resources. While open cut mining has always been practised by humans, pre 1945 it was mostly small scale due to the lack of technology. The size of the mines and the landscape scale over which it is conducted is only possible now due to modern technology that allows the earth's surface in most cases to be firstly broken up with explosives and secondly, this broken up material removed in a cost effective way by large machinery. The technology and efficiency to access a resource is continually improving as well as mines and their size becoming large in both surface area and depth. The scale of the new land transformation (abiotic change) is so large and new that there are no fully tested rehabilitation solutions for such large scale scenarios (Hobbs et al., 2006, 2009).

A completely new abiotic and biotic landscape is inevitable in open-cut mining (Doley and Audet, 2013). The extracted material surrounding the mineral of interest, termed waste rock, can either be placed back in the mined out pit or a new landscape created at or around the pit. In coal and metallic mining the waste always has a greater volume than what it had pre-mining due to the breaking up of the material and the creation of air space or voids within the previously intact and coherent geological structure. This increase in volume of waste, called swelling, ensures that any new landscape will sit proud above the pre-existing landscape. A rule of thumb is that waste material increases in volume by approximately one-third over that of the undisturbed material. However, in many other scenarios, such as hard-rock quarries, gravel pits, or mining in different loose sedimentary material, the situation is the opposite, since the volume of the extracted

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raw material is either missing in the end, for example, if most of the rock is beneficial product. In these scenarios, topographical depressions, frequently with lakes at their bottom, are the post-mining landscape to face.

Surface mining has considerable long-term impacts. With coal and metallic open cut mining, both during and at the cessation of mining, there is the environmental impact of the pit or void, which is often very large and deep. The pit has a strong influence on both shallow and deep groundwater (Hancock et al., 2005). During mining this infilling groundwater has to be managed while at the cessation of mining the pit will infill with groundwater, taking up to centuries to stabilise water levels. The final pit or void is a legacy issue that requires special consideration in its own right and is only briefly discussed above here.

For geomorphology and ecology, the undisturbed (pre-mining) landscape has evolved over geological time with an accompanying ecological community that has optimised to the specific geological, pedological and climate environment. Post-mining, the waste rock material is always different to that of the pre-mine surface material. With new and different materials on and below the surface come different soil physics and hydrology with resultant differences in soil water holding capacities, runoff properties, as well as different soil chemistry and groundwater (Nicolau, 2003a). In metallic and coal mining, in conjunction with this change in soil properties are steeper slopes and longer slope lengths as a result of the increase in the volume of the waste material. These increased slope angles and lengths produces increased erosion (Nicolau, 2003b). Therefore it is highly unlikely that the post-mining landscape ecology will or can be the same as the premining conditions (Doley and Audet, 2013). In addition, unweathered bedrock is also exposed, both in highwalls and pit benches, producing different slopes and surfaces with different physical and chemical properties to that of the pre-mine landscape.

For all the aforementioned reasons, there is at present a growing momentum for considering geomorphic principles in mine rehabilitation, the core of this review paper. This is addressed as a general intention or attempt that a reconstructed 'minescape' should have similar functions to that of a natural geomorphic system. Specifically, the one that can be best geomorphically fitted, given the new post-mine conditions. This requires that the new landscape has hillslope lengths, gradients and shapes similar to that of a natural system with both hillslope and channel having the necessary and geomorphologically efficient non-linear curvature. Moreover, the design and construction of a new drainage network is based on geomorphic principles (Sawatsky and Beckstead, 1996), so that steep rock lined ditches can be replaced by natural-functional streams (OSMRE, 2017). In other settings, a mine highwall can be transformed into a 'natural' cliff. This of course is not always the goal, since other end or land uses not demanding this approach can be the aim (Pearman, 2009).

1.1. The goal for post-mine landscape reconstruction

It is essential to ensure that water and sediment flows from the new landscape are abiotically and biotically optimised for the disturbed system and the flows integrate with the surrounding landscape. To reach this state it is required that the landscape have a growth medium (i.e. soil) that allows flora and fauna to recruit, occupy and evolve as well as to seamlessly move from the natural surrounds to the post-mining landscape. The ultimate goal is a landscape that is ecologically (restoration) (McDonald et al., 2016) indistinguishable from its undisturbed surrounds. However, there are questions as to whether this is possible as:

1. The waste rock will be very different to that of the natural surrounds (and of the pre-mining landscape) (Doley and Audet, 2013). In some cases recovered topsoil is placed over the waste rock to aid revegetation – but whether it will be waste rock or waste rock with a topsoil cover, it will be very different to the natural surface (either pre-mine or surroundings of the mine). Therefore different ecological communities and processes are likely to operate at least in the initial years post-mining (Hobbs et al., 2006).
2. The material and landscape is 'new' in that it has been created 'de novo' (Doley and Audet, 2013). All materials and hillslope shape are new and there is very little knowledge as to how the new material will evolve and at what rate. That is, how will new soil form, at what rate and what will the soil evolve to? For example, waste materials can have very different pH and chemical composition to that of the pre-mine surface. Therefore assuming success of a post-mining landscape rehabilitation is not a short-term consideration. The evolution of the surface in terms of soil development (or pedogenesis) may take decades or centuries to occur with the flora and fauna evolving in concert (Cohen et al., 2009).
3. How do starting conditions (i.e. surface slope, slope length and materials) and resultant hydrology and initial vegetation influence landscape trajectory? If one method or pattern of rehabilitation is undertaken, does this affect the soilscape reconstruction?

Is there equifinality? For equifinality all soilscape reconstruction will ultimately be very similar for a particular environment and medium?

The materials that the new surface is constructed from are very different to that of the original surface. Physically, the material may be very rocky which may be a very erosionally stable material but too coarse to hold water and therefore will limit plant growth (Fig. 1). In other scenarios, bedrock or loose sediments outcrop at the bottom of closed pits (Wirth et al., 2012).

In almost all situations, the new exposed materials will have very different physical and chemical properties and therefore will weather to a different soil to that of the pre-mining and surrounding landscape surface. This is the case, for example, of shale, schists or different types of saprolite. Many of these rapidly weathering materials are highly erodible and may contain high levels of salts, which impede vegetation establishment (Fig. 2). There is also poor knowledge about the weathering behaviour of the waste rock and how this will affect the evolution of the new landscape (Wells et al., 2006, 2008). Nicolau (2003b) reports investigations by Martin Haigh in which accelerated erosion occurred on initially successful pasture restored in Welsh coalfields, as a consequence of weathering of waste shale and formation of an impervious clay layer in the soil at the depth of 30 cm. The goal at sites such as this is to identify the materials during the extraction process and burying any suboptimal materials deep within the waste rock dump (WRD) surrounded by inert non-hostile materials. This encapsulation process ensures that many waste rock dumps are relatively tall. Therefore at almost all sites the landscape has taller and steeper slopes. The alternative is to have a less tall landscape with lower slopes – but this increases the new landscape footprint.

All mines seek to disturb the smallest footprint possible. Increasing a mine footprint is something that is usually avoided as the financial bond placed on a mine is usually based on the amount of area disturbed. Another reasoning is that if there is less disturbed area, then there will be fewer rehabilitation problems. However, fixing the dump toe limit to some arbitrary line is not always beneficial, and in some cases better results may be achieved if the toe or footprint could be expanded. For example, a proposal (approved in 2017) for a geomorphic-based rehabilitation of a coal mine in Colombia extended the toe disturbance limit of an out-of-pit waste rock dump slightly, but provided a functional geomorphological integrated landform that overcomes the problems of the traditional reclamation landforms (Bugosh et al., 2016; Fig. 3). Therefore rehabilitation (McDonald et al., 2016) to another optimally functional system may be the only possible outcome. But there are situations where increasing the mine footprint is not possible. This happens where the slopes are steep and the space is limited. This situation is typical for mines in mountainous areas (Martín-Moreno et al., 2018). Expanding a mine footprint is usually impossible in

Fig. 1. Waste rock with very large particle size (left hand side) and less large on right hand side. Monitoring has found the materials to be erosionally stable but with little capacity to support plant growth due to the lack of fine material – the limitation being water holding capacity of the material.

densely populated areas (i.e. Europe). Therefore, this discussion is more relevant for regions with low population density.

1.2. The catchment scale/dimension

Open cut mining can obliterate the pre-mine drainage networks that have evolved over geomorphic time (Kite et al., 2004). A common approach is to use engineered structures to manage runoff (Fig. 4). At a landscape scale, the most important issue to be addressed in rehabilitated areas is the management of runoff. A poor understanding of the fact that most of the land surface is organized according to catchments, or drainage basins, and that any disturbed landscape will try to re-establish a new drainage network post-mining leads to common failures, mostly by gullying (McKenna and Dawson, 1997). Gullying is a symptom of those adjustments of the geomorphic system as it tries to redevelop a new drainage network (Sawatsky and Beersing, 2014; Fig. 5).

Many drainage networks of the earth's surface have a control imposed by the geological structures (e.g. faults, joints, strata). Some natural drainage networks do not have such control of the bedrock structure. In non-consolidated recent sediments, or homogeneous materials they usually have a 'dendritic' form (Dunne and Leopold, 1978).

Fig. 2. Fine grained and rapidly weathering material (dark grey on left and light grey on right). Both materials are hostile to plant growth due to high salt content. The red-brown material is soil and saprolite and supports vegetation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

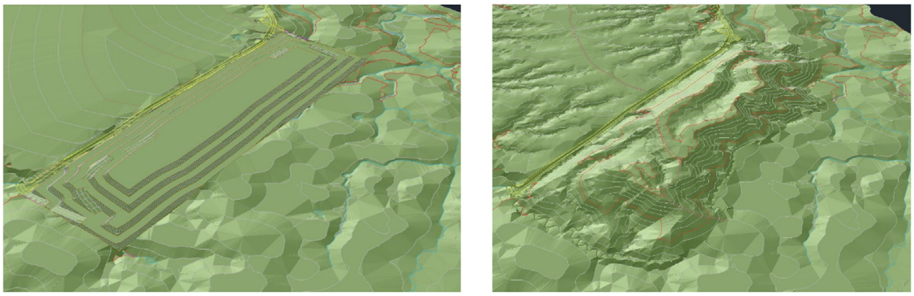

Fig. 3. Left, traditional mine rehabilitation landform; right, alternative geomorphic (GeoFluv) rehabilitation landform. Coal Bijao project mine, SATOR S.A.S. (Argos Group) Puerto Libertador (Córdoba, Colombia). The Traditional reclamation landform shown in the left has a minimized disturbance footprint in an out-of-pit waste dump. The minimal footprint leads to piling the waste material as high as possible which leads to a terrace and downdrain landform that is very unstable against erosion, which provides minimal reclamation land use benefit, and which many consider an unsightly monolith on the landscape. Also, it reduces variation in storm water harvesting and sunlight exposure that will lead to less diversity in vegetation species and composition. For this case, the geomorphic alternative design for the same area (right) has benefitted by extending its toe as needed to accommodate the volume of waste material needed to make the valleys required to convey storm water runoff without the accelerated erosion that is often a problem with traditional terrace and downdrain landforms. In addition, potential land uses are maximized, and ecological and visual benefits are also evident. Figure reproduced with the kind authorization of SATOR (Colombia).

In terms of rehabilitation, it should be understood that most of the pre-mine drainage networks have such geological structure control, whereas post-mine landscapes on waste rock will tend to develop dendritic networks (Bugosh, 2004).

In most cases, mining takes place in an environment where there are imposed geological controls and these structures will not generally be reflected in the post-mining environment.

1.3. Off-site impacts

As discussed above, a newly constructed landscape will have no vegetation (at least initially), and will likely have taller and longer slopes than the pre-mine landscape. Post-construction may it take many months for vegetation to successfully establish, for mined surfaces to armour and exert erosion control. The landscape will therefore immediately have a relatively higher erosion potential, and this high erosion may inhibit vegetation recruitment and establishment (Moreno de las Heras et al., 2011). During the mine operation, any visible erosion features such as gullies can be fixed, unsuccessful revegetation addressed (i.e. due to poor rainfall) and general maintenance of erosion control features conducted. In particular, gullies, while their visual impact is seen to be concentrated in small areas, can remove huge volumes of emplaced material. Gullies will also depressurise any shallow groundwater system leading to both loss of soil water and nutrients.

This high initial erosion can lead to pollutants, sediment and nutrients being delivered to downslope reconstructed areas as well as leaving the site. The use of retention ponds/basins can help managing this in the short-term, however these will eventually fill with sediment and therefore require maintenance. They are not a long-term geomorphological solution for sites with erosionally unstable hillslopes. High erosion can therefore create off-site contamination (Nicolau, 2003b).

2. Sound references sites and geomorphic analogues

The primary question when facing the recovery of a mine site should be what is the desired land use and ecosystem functions that have to be re-established again after mining. Those final land use targets are indeed quite broad (Pearman, 2009) and range from more direct human focussed outcomes (e.g. parks, food or timber production) to more 'nature conservation' oriented this being beneficial for humans in terms of restoring ecosystem services (Prach and Tolvanen, 2016).

Fig. 4. An engineered channel on a post-mining landscape.

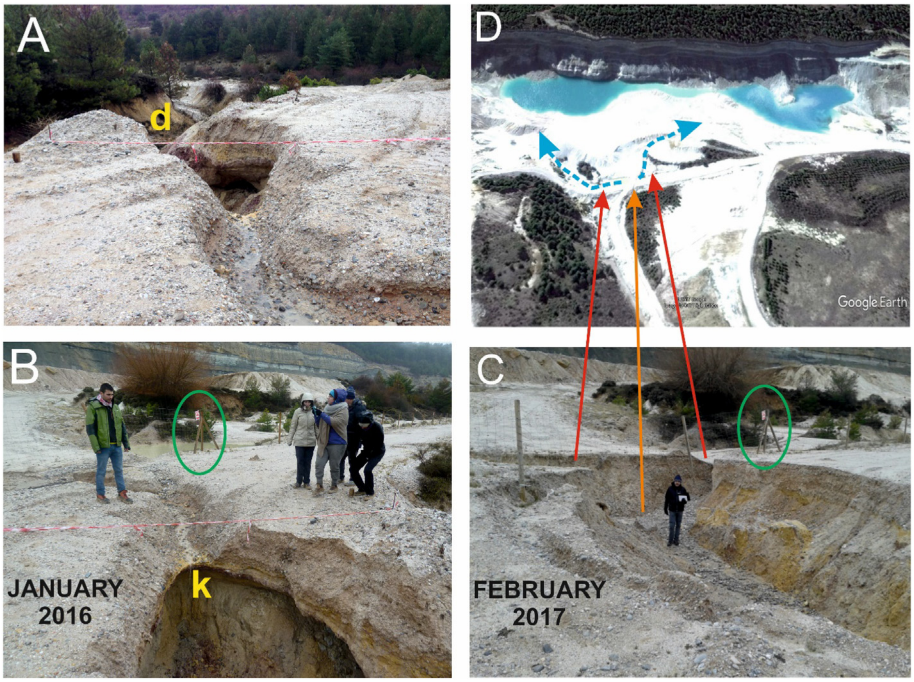

Fig. 5. Accelerated headcut gully erosion within the abandoned kaolin Nuria mine, in Central Spain, involving high flash flood risk hazard. A) Downstream view of the head of a gully, cutting an existing haul road, as a consequence of the drainage network redevelopment from the ditch (d) of the haul road. B) Position of the knickpoint (k) in January 2016. This photo shows the same location of photo A, but in opposite direction. C) Same location that B in February 2017; the knickpoint has migrated upstream about 20 m in length and about 2 m in depth in 13 months, cutting completely the haul road. Note the fence post within the green ellipse for comparison. D) At the location of the person in photo C, the gully has developed two branches, which are head cutting towards a large pond located at the foot of the highwall of the former mine (blue arrows). If the headcut reaches the pond, a flash flood will occur, risking a village, a main road and a natural park located downstream of this location. The mine is abandoned (with no rehabilitation). But even a proper rehabilitation, with successful soil and vegetation recovery, but lacking to understand this process, would have likely led to the same results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1. Current practice

A common practice for new mine landscapes is to construct stand-alone WRDs (Fig. 6; Orman et al., 2011). They are constructed in different physiographic locations to simple linear designs (with a number of 'lifts' of usually 10 m steps) with 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 minimized. 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 (downdrain) channels are constructed (Fig. 4). There is also little consideration as to how these landscapes will mature through time.

Landform design in mine rehabilitations (using linear or terraced landforms), even with successful vegetation cover, are often not stable in the long term (Martín Duque et al., 2010). Most commonly, benches and contour-graded banks are prone to failure, leading to severe gullying. Prach et al. (2011), from analysis of multiple mine sites in the Czech Republic, have demonstrated how conventional approaches (called 'technical measures') represent mostly expensive and ecologically misguided approaches that often decrease biodiversity. In comparison with spontaneous succession in non-rehabilitated sites, these conventional measures produce landforms with less topographic and habitat diversity.

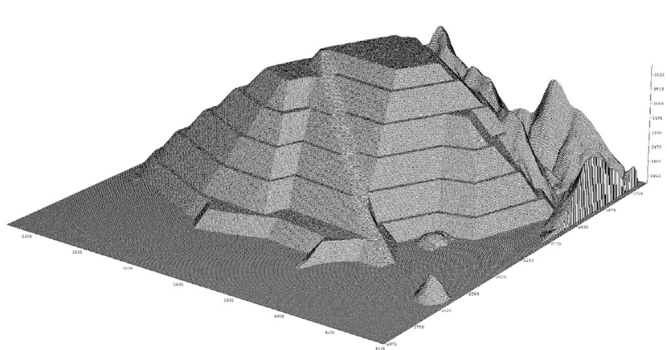

Fig. 6. A proposed stand-alone waste rock for a metalliferous mine in semi-arid northern Australia.

Unique landscapes for mines are Tailings Storage Facilities (TSF). These are dams that contain fine material from the mineral processing and are usually wet, highly erodible and often contain contaminants. They can be stand-alone structures or accommodated into the natural landscape (valley fill). However, given their content, they need to be erosionally stable where the potential risk for dam failures or acid drainage (a common issue) is reduced (Johnson and Hallberg, 2005). Here, the main aim is isolation, rather than an integration with surrounding landscapes, but this issue is starting to be resolved with promising results (Slingerland et al., 2019).

2.2. Functional and non-functional landscapes

There is a danger that anything that deviates from the current linear construction will be called geomorphic design. For example, trying to imitate surrounding or pre-mine scalloped landforms is a type of well-intentioned landscaping work, but lacks scientific basis. The authors have observed this type of design by consultants worldwide, with little holistic and scientific understanding of hillslope and catchment processes (i.e. geomorphology). Geomorphic research using natural landscapes can now link hydrology and erosion process to the landforms and drainage network quantitatively (Willgoose, 2018); for instance, slope gradient with catchment area (Willgoose et al., 1991), drainage network geometry (Perera and Willgoose, 1998), spatial distribution of elevation (Willgoose and Hancock, 1998), and spatial distribution of erosional energy (Ibbitt et al., 1999). These links between catchment processes and geomorphology suggest fundamental properties of constructed landscapes that need to be replicated and how they vary between natural and post-mining landforms. Often, looking good at the beginning will lead to widespread erosion. The most serious consequences of this approach are that they frequently lead to general instability, with serious liability consequences for all involved.

The authors interpret that this attempt to 'recreate' the natural landforms that surround a particular mine in its rehabilitation process comes from the Approximate Original Contour (AOC) concept included in the Surface Mining Control and Reclamation Act, SMCRA, 1977 (United States). This law states (p. 114): "AOC means that surface configuration achieved by backfilling and grading of the mined area so that the reclaimed area, including any terracing or access roads, closely resembles the general surface configuration of the land prior to mining and blends into and complements the drainage pattern of the surrounding terrain…". However, it should be noted that much of the science underpinning current work post-dates the publication of this document.

For many years, the AOC implementation did not produce the desired results. Several authors (Brenner, 1985; Bell et al., 1989; Zipper et al., 1989) report that the near-universal use of the AOC requirement in the steeply sloping topography of the Appalachian region was not appropriate, and that it led to common slope instability, excessive mining costs, increased erosion and loss of post-mining land-use value. The main reason for failures triggered by a narrow interpretation of the AOC concept was that the nature of the mining waste rocks (non-consolidated) was entirely different to that of the pre-mining conditions (almost always consolidated rocks). Post-mine landforms need to be, in most situations, different to pre-mine landforms and need to be designed to establish and maintain hydrologic and ecosystem functions in landscapes developed on non-consolidated material. The geomorphic approach to mine rehabilitation is first and foremost directed by the need to establish a landform that functions similarly to a mature, stable natural landform that is not subject to accelerated erosion. This means that achieving functionally stable landscapes with unconsolidated wastes, requires different approaches to be followed. Effective solutions have to be developed around sound and scientific geomorphic solutions and modelling. Some regulatory bodies, such as those in New Mexico in the US, have already accepted this "change of direction from AOC" to geomorphic reclamation on the described basis (see NMMMD, 2010).

It needs to be recognised that the current practice of trying to replicate natural landforms that have evolved on consolidated rock with the same landscape (but now constructed on unconsolidated material) seems to have played an important role in the growing influence of landscaping, as used in landscape architecture. For example, in the text *Landforming*, Schor and Gray (2007) demonstrate landscape architecture has positive outcomes for new urban developments. The conflict arises when these general approaches of landscaping and landforming are intended to be applied in large mining areas without geomorphic principles. This occurs because of a lack of knowledge as to the basic principles that operate (i.e. fluvial processes) within a catchment and without the knowledge on how the change in physical and chemical properties affect the potential of rehabilitation of minescapes (Toy and Chuse, 2005).

3. The development of geomorphic rehabilitation – a brief history

The demand for introducing geomorphic principles in mine rehabilitation developed in the US, UK and Australia in the late 1970s and early 1980s. The US SMCRA (1977) can be considered the first text in this regard, asking for the need for complementing the drainage pattern of the surrounding terrain. It actually introduced a 'catchment approach' in mine rehabilitation — using the drainage basin as the fundamental unit for planning mine rehabilitation and guaranteeing hydrological connectivity. This approach was explicitly expressed later by Stiller et al. (1980), who asserted that planning for long-term stability of reclaimed surface mines meant incorporating drainage networks that would integrate into the surrounding landscape. A little later Toy and Hadley (1987) and also in the US, this new discipline had already its own book, *Geomorphology and Reclamation of Disturbed Lands*, by Toy and Hadley. After 1990, the US scientific literature relating geomorphic reclamation of disturbed lands grew (i.e., Toy and Black, 2000; Toy and Chuse, 2005; DePriest et al., 2015; among many others).

Furthermore, specific classifications, tools and software were developed in the US for geomorphic rehabilitation of mined sites. The Rosgen (1994, 1996) morphological classification of rivers is in itself a geomorphic reconstruction method. This approach has been widely employed for perennial stream reconstruction in the United States, including mined sites. The updates and learnings since the implementation of the AOC concept were also the breeding ground for the reclamation method GeoFluv™ — from Geomorphic and Fluvial (Bugosh, 2000, 2003). GeoFluv (discussed in detail later) is a geomorphic method for land rehabilitation that is able to reproduce the complexity of natural landforms and drainage networks within catchments, which become the basic rehabilitation design units. This technique began to be applied at large coal mines of New Mexico (United States) in 1999. Natural Regrade is the commercial software (Carlson software, 2019), launched in 2005, that helps users to efficiently make GeoFluv designs in a CAD format. GeoFluv through Natural Regrade has been successfully used in the US (Bugosh and Epp, 2019). RIVERMorph (2016) is a design software based on the principles established by Rosgen (1994, 1996). Today, Geomorphic Reclamation is officially recognised within the OSMRE Technology Development and Transfer (TDT) program (http://www.osmre.gov/programs/TDT.shtm), and states as New Mexico have a regulation that considers that a geomorphic approach to backfilling and grading is the Best Technology Currently Available (BTCA) for stabilizing coal mine reclamation (NMMMD, 2010).

Australia pioneered also the geomorphic and catchment approaches to mine rehabilitation, with the book *Mine Rehabilitation* (Hannan, 1984). These geomorphic principles were later extensively developed in the handbook *Landform Design for Rehabilitation* (Environment Australia, 1998). In parallel, and mostly due the application of the Landscape Evolution Model SIBERIA for landform design in mine rehabilitation, Australia developed the most extensive set of both scientific (papers and books) and industry handbooks dealing with landform design in mine rehabilitation. Benchmark papers appeared in the mid-1990s (Evans and Riley, 1994; Riley, 1995a, 1995b; or Willgoose and Riley, 1998a, 1998b, among others). This literature body was largely extended from the 2000s up to now (Hancock et al., 2003; Hancock and Willgoose, 2018).

In Canada in the 1990s mine rehabilitation based on a geomorphic approach commenced (Keys et al., 1995; Sawatsky and Beckstead, 1996). The contributions of the Canadian practitioners are exceptional, mostly as an outcome of application for more than 25 years at the Oil Sand Regions (OSR) of Alberta (Canada). Almost all oil sands mines have closure plans that feature a geomorphic approach. Also at coal mines of Western Canada and United States. Sawatsky and Beersing (2014) provide a good synthesis of the Canadian geomorphic approach to mine rehabilitation.

In Europe, specific examples and publications on Geomorphic Mine Rehabilitation come mostly from the United Kingdom, Spain and France. In the United Kingdom, a method for replicating natural landforms at hard rock quarry faces was developed in the late 1970s (Humphries, 1977, 1979), and continued for the same mine setting with work of the Limestone Research Group of the Manchester Polytechnic (Gagen and Gunn, 1988; Gunn et al., 1992). In Spain, scientific applications and literature in this field started to appear at the end of the 1990s and continued since then (Martín Duque et al., 1998; Nicolau, 2003a; Martín Duque et al., 2010; Zapico et al., 2018). The main application of Geomorphic Mine Rehabilitation in Europe is in kaolin and silica sand mines and limestone and clay quarries in Spain. It has been recognised at the European level by means of recognising Geomorphic Reclamation as one of the Best Available Techniques for the Management of Waste from the Extractive Industries (JRC, 2018). Finally, in France, the Talus Royal method has been successfully applied at rock roadcuts in France (Génie Géologique, 2020) and is starting to be applied in rock highwalls at quarries. This method is convergent with the one in the United Kingdom and attempts to compress time by designing and building the 'natural' rock cliffs or scree (talus) slopes that would tend to form and evolve with time, through falls and slides that occur preferentially on weathered or fractured rocks. Equivalent natural cliffs or rock slopes are used as analogues. In Table 1 we have compiled our own synthesis of geomorphic landform design methods, along with soil

Table 1
Synthesis of Geomorphic landform design methods and Soil erosion and Landscape Evolution Models, and related software, for mine rehabilitation.

Approach	Method	Related software	First and key references/website	Year	Main countries
I. Geomorphic landform design methods					
1. Fluvial Geomorphic approaches *for designing drainage systems and related hillslopes, at watershed scale, in non-consolidated materials*	1.1. Rosgen	RiverMorph	Rosgen (1994, 1996) http://www.rivermorph.com/	1994	United States
	1.2. Design of Sustainable Drainage Systems		Sawatsky and Beckstead (1996); Sawatsky and Beersing (2014)	1996	Canada
	1.3. GeoFluv™	Natural Regrade	Bugosh (2000, 2003); Bugosh and Epp (2019) http://www.carlsonsw.com/solutions/mining-solutions/natural-regrade/	1999	United States, Spain, Australia, Colombia
	1.4. QUEL		Ibbitt et al. (1999); Willgoose (2001)	1999	Australia
2. Hard-rock Natural Landform Replication *for designing landforms characteristics of hard-rock natural cliffs, valleysides, steep slopes*	2.1. Landform Replication in hard-rock quarry faces		Humphries (1977, 1979) (Gagen and Gunn, 1988; Gunn et al., 1992)	1977	United Kingdom
	2.2. The Talus Royal[R]		http://www.2g.fr/	1995	France
II. Soil erosion and landscape evolution models					
3. Soil Erosion Models *Provide erosion rates at the hillslope scale, do not actively adjust the hillslope through time*	3.1. RUSLE	RUSLE 1.06, RUSLE 2.0 (for mining, construction and reclamation lands)	https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/research/rusle2/revised-universal-soil-loss-equation-2-overview-of-rusle2/ Toy et al. (1999)	1999	United States Australia
	3.2. MUSLE - IECA		Fifield (2004)	1994	United States
	3.3. WEPP	WEPP	https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/wepp/research/ Laflen et al. (1991)	1991	United States Australia
	3.4. SEDCAD	SEDCAD	http://www.mysedcad.com/	1987	United States
4. Landscape Evolution Models *Provide erosion rates, type of erosion and actively adjust the hillslope and provide 3D visualization of evolving landform*	4.1. SIBERIA	SIBERIA, MOSCOW	http://www.telluricresearch.com/siberia-homepage.html (Willgoose, 2018)	2018	Australia
	4.2. CAESAR-Lisflood	CAESAR-Lisflood	https://sourceforge.net/projects/caesar-lisflood/ (Coulthard et al., 2013)	2013	United Kingdom, Australia

erosion and landscape evolution models, and related software, for mine rehabilitation.

4. Geomorphic principles and analogues

Open cut mining removes topsoil, breaks underlying horizonisation and geological structure eliminating any organization that has developed over geological time. With that geological age and structure comes soils which have coevolved with vegetation, climate and biology (Butler, 2007).

The question then is, what do you use as a geomorphic analogue to guide landscape reconstruction? Trying to replicate the surrounding undisturbed landscape will be impossible, as the physical and chemical structure of the reconstructed landform will be very different, as we have previously discussed. Further, there will be no reconstructed mine sites of sufficient age from which long-term geomorphic attributes or landscape trajectory can be determined from. However, the natural surrounding landscape can provide guidance in terms of to the most stable and lowest energy system.

Natural landforms and landscapes follow universal geomorphic principles. Outside a few environments (such as high mountains and deserts or sand deserts), or specific hard-rock landforms (such as cliffs), most of the Earth's ice-free land surface is organized in drainage basins, which have been shaped mostly by fluvial and hillslope processes. They are comprised of streams, hillslopes and divides, all of which interact with one other. Stiller et al. (1980) have claimed that the drainage basin should be used as the fundamental planning unit for mine rehabilitation. The referred natural hillslopes are never linear with constant gradient. On the contrary, they universally have convex profiles at the top of a slope and change to concave as the hillslope length increases (Environmental Australia, 1998). Stream channels rarely have planar longitudinal profiles, but become progressively steeper as one moves upstream, and the width and depth having evolved to match the upslope catchment area. When following geomorphic principles in mine rehabilitation, stream longitudinal profile gradients should be progressively steeper upstream and flatter downstream, mirroring stable natural channels (Environment Australia, 1998). Also, the natural channel geometry is based on bankfull discharge, and have different width-to-depth ratios and sinuosity depending of the stream types (Rosgen, 1994, 1996). The geometry of natural meandering channels is not random. It follows moderately understood mathematical relationships between bankfull width, radius of curvature of meanders, meander belt widths and meander wavelengths (Leopold and Wolman, 1960; Williams, 1986). The use of such fluvial geomorphic principles in mine rehabilitation has been and is common in the United States and Canada. Sawatsky and Beckstead (1996) offer also universal fluvial geomorphic principles that have been successfully used in the Canadian oil sands restoration: (a) floodplains and meandering channels significantly reduce flow velocities; (b) instead of rigid bed and banks, designed 'natural' streams have a mobile bed composed of natural armour, which moves in response to flood events; (c) despite the high rates of changes that may occur, replication of natural channels is more sustainable, and far superior to most rigid-engineered drainage systems. The GeoFluv method (Bugosh, 2000, 2003; Bugosh and Epp, 2019), gathers and synthetizes most of these fluvial geomorphic principles, to be used in any land reclamation involving earth movements. The method complements them with other quantitative morphological parameters that define natural drainage basins (Horton, 1945), such as drainage density, length of overland flow (distance from ridgeline to channel's head), or scalloped hillslope topography at upland areas, among others.

The use of natural analogues in mine rehabilitation results in a significantly higher landform and habitat diversity (complex convex-concave hillslopes, with different aspect, cliffs, valleys, wetlands) compared to conventional landform design, which results in very homogeneous topography. Therefore, the use of geomorphic landform design has demonstrated to have advantages from a biodiversity point of view (Fleisher and Hufford, 2020).

The ideal situation is to use a local disturbed system, however, modern mining using the methods at the scale described here has no current long-term analogue which can be used. Moliere et al. (2002) attempted to quantify rates of change for hydrology and sediment transport for new (0–2 year old surface), 50 year (post-mining) and geological age surfaces. This has been the only documented field based approach to examining new surface change and the role of vegetation determine analogue systems (Hancock et al., 2016b). Using modelling methods, Sharmeen and Willgoose (2007) and Hancock et al. (2015a, 2015b, 2016a) have shown that erosion rates can take centuries to reduce on post-mining landscapes. They suggested that landscapes modelled over geological time may be used to infer more stable initial landforms.

One option is still 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 (Fig. 7).

At some sites geomorphological analogues have been sought. The ERA Ranger mine in the Northern Territory, Australia has been the focus of intense environmental scrutiny due to its location surrounded

Fig. 7. A reconstructed landscape with benches and contour banks and initial revegetation. Rills and gullies can be observed (top). A partially rehabilitated hillslope with benches and contour banks displaying the underlying material and initial dump shape (bottom).

Fig. 8. ERA Ranger mine trial landform 3 years after construction (top) and the Tin Camp Creek natural landscape (bottom).

by the World Heritage listed Kakadu National Park. The site has two open pits which will be infilled and a tailings dam which will be removed. The mine has operated since the 1980s and plans for rehabilitation began at this time.

Here a potential analogue site, Tin Camp Creek, was found which is geologically and geochemically similar to that of the Ranger mine waste (Riley and Rich, 1998) (Fig. 8). This site has been extensively examined as a geomorphic analogue where its erosion rate, hydrology and long-term evolution has been a focus (Hancock et al., 2002; Moliere et al., 2002; Hancock and Evans, 2010; Hancock and Lowry, 2015; Hancock et al., 2016a, 2016b, 2016c).

While the geology at Ranger is geochemically similar to Tin Camp Creek, there is no guarantee that the Ranger materials will follow the same weathering and soil development path as that of the natural landform. There is also no guarantee that flora and fauna will evolve to similar ecology. Finally, there is a soil structure and underlying bedrock base at Tin Camp Creek which will be absent at Ranger (Fig. 8). In terms of rehabilitation landscape shape and form, geomorphic analogues have been sought from the surrounding landscape, however the topography of the rehabilitated site will be constrained by the bulking of the material as well as the desire to fill in two pits and remove a tailings dam and its content. There are no immediate geomorphic analogues surrounding the site for this large-scale reconstruction (Fig. 9).

Other approaches for suitable geomorphic analogues in mine rehabilitation have been:

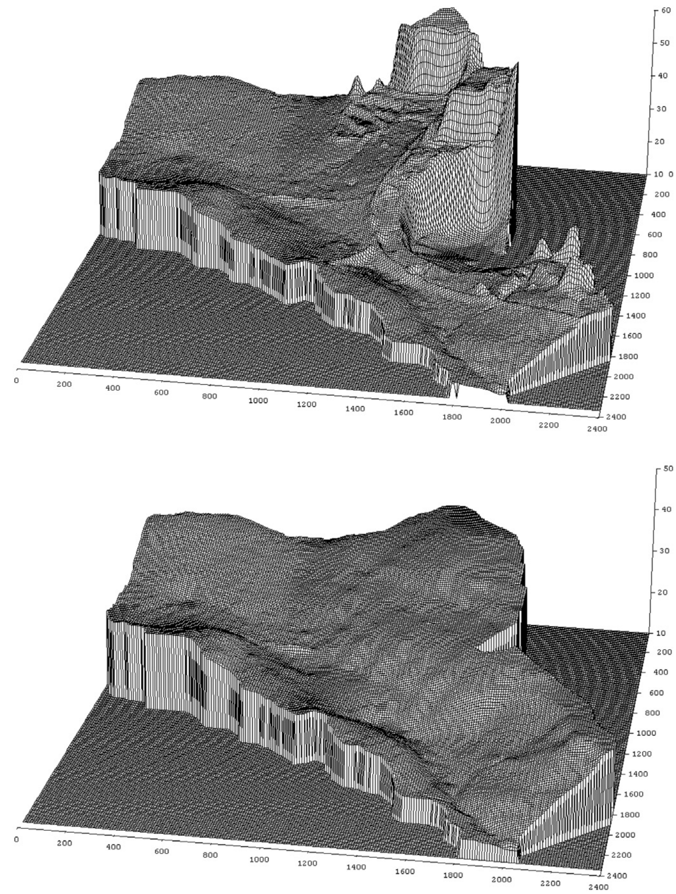

Fig. 9. Digital elevation model (10 m grid) of Corridor Creek for the current mine site with mined out pit and stockpiles (top) and potential post-mining landform design (bottom). All dimensions are metres.

(1) For waste rock, identifying mature (stable) geologic landscapes developed on unconsolidated earth materials (mostly surficial deposits) similar to those of the waste rock dumps, shaped over thousands of years in similar climate conditions (i.e., alluvial or fluvial terrace, colluvium or landslide deposits, among others). This approach is mostly used by the GeoFluv method (see further sections). Despite the uncertainties associated to the similitudes of physical of chemical properties between the natural analogue and the waste rock, this approach has proved being successful (Zapico et al., 2018; Bugosh and Epp, 2019).

(2) For consolidated bedrock at highwalls and benched terraces, natural cliffs developed over thousands of years on the same type of rocks, gradients, aspects and climate provide analogues. This approach is mostly used for replicating natural landforms at hard rock quarry faces (Gagen and Gunn, 1988; Gunn et al., 1992) and by the Talus Royal method (Génie Géologique, 2020).

5. Vegetation and landscape evolution

Many mine sites are reliant on vegetation for their erosional stability, so that successful rehabilitation is equated to successful revegetation. Stiller et al. (1980) noted almost 40 years ago that successful rehabilitation includes revegetation, but that "revegetation and erosion control are not simply cause and effect" (Stiller et al., 1980, p. 274). Any landscape system should have topography that is erosionally stable with vegetation providing the foundation for ecological succession as there is no guarantee of regular rainfall to maintain acceptable vegetation covers. It is under a drought and fire scenario that a slope reliant on vegetation (for erosionally stability) then becomes unstable. It is largely unknown how reconstructed landscapes perform after fire. Relying only on vegetation to stabilise slopes is a high-risk strategy, and post-mining landforms should provide the best tool for erosion control, thereby enhancing revegetation efforts (Stiller et al., 1980).

Choice of vegetation and groundcover is very important. While it has been shown that native trees can be established on many sites, outside temperate climate regions they provide little groundcover and thus little erosion protection. A mix of grass, trees and shrubs provides diversity, however it is grass that provides the most robust erosional stabilisation. In areas such as the Hunter Valley (NSW, Australia) the majority of coal mining areas are in former beef cattle grazing areas, which are largely grassland with patches of eucalypts. Many of the soils have only a shallow A-horizon underlain by a heavy clay B-horizon. Therefore the agriculture potential of the undisturbed or pre-mining landscape is limited. Also, the landscape was highly modified by land clearing and in many areas this has resulted in soil erosion and dryland salinity. A goal is to re-establish this type of vegetation pattern. Initial results over several decades suggest that this may be possible, however, will this system be maintained in future decades and centuries and can it recover from fire?

For many sites (such as the Hunter Valley) the potential is there for any reconstructed landscape to have a higher biological productivity post-mining to that of the pre-mining landscape as any clay horizons and bedrock have been removed with the emplaced waste rock providing what is effectively an infinite soil depth. Theoretically, this infinite soil depth can capture all rainfall allowing maximum soil water storage. The ability to capture and hold water allows an optimal vegetation system to evolve. However, this assumes that the material can capture and hold water as well as having no physical or chemical constraints (Figs. 1 and 2).

6. Pre and post-landscape design and assessment – models and modelling

In complex non-linear systems where there are a number of potential outcomes (Hancock et al., 2016b), models are extremely useful. Models generally incorporate the most important landscape drivers or variables that are likely to have a first-order influence on the system of interest. In landscape systems the variables are hillslope length and angle (topography), rainfall and runoff (climate) and material properties (i.e. erodibility of the surface material and vegetation interaction) (Tucker and Hancock, 2010; Willgoose, 2018).

6.1. Landscape evolution models

There are a number of models and modelling approaches that can be employed for post-mining landscape assessment with a compilation in Table 1. The most widely used model is the Universal Soil Loss Equation (USLE) and its derivatives such as the Revised Universal soil Loss Equation (RUSLE). It has been used globally for many decades and has proven to be a useful and reliable tool (Wischmeier and Smith, 1978; Flanagan and Livingston, 1995). Given its global use, model parameters and data sets can be easily found or more reliable parameters can be determined from site specific data. However, a disadvantage is that the RUSLE only models erosion, not deposition, and only provides average erosion. A hillslope is assumed to be uniform and does not indicate where erosion occurs on the hillslope. Other models such as the Water Erosion Prediction Program (WEPP) include a climate function, vegetation and plant growth functions and hillslopes can be mathematically linked to form multiple hillslopes (Flanagan and Livingston, 1995). However, these models neither evolve the landform nor properly consider gully erosion, and it happens that, in post-mining landscapes, the majority of erosion occurs by gullying caused by fluvial erosion (Hancock et al., 2000, 2013), in a process of redevelopment of a drainage network.

Landscape evolution models represent the next evolution of modelling technology. They offer all the functionality of the USLE/RUSLE and WEPP but operate on a digital elevation model (DEM) grid. They calculate both erosion and deposition at each DEM grid cell and adjust elevation accordingly. In this way the landscape can evolve through time (Tucker and Hancock, 2010; Willgoose, 2018). This landscape evolution allows not just erosion rate to be determined but also where erosion and deposition occurs. The models can also visually show what the form of erosion is (i.e. sheetwash, rilling, gullying) (Hancock et al., 2013).

These models are particularly useful for assessing pre-mine landscape design. A landscape design can be input into the LEM and allowed to evolve. Models such as SIBERIA (Hancock and Willgoose, 2018) are ideal for assessing landscapes at annual time steps and can be run for thousands of years (Hancock et al., 2016b) while models such as CAESAR-Lisflood (Coulthard et al., 2013) can run at hourly time steps and can assess the effects of storm events on erosional stability.

As the models allow calculation of both erosion rates (i.e. t/ha/yr) as well as erosion type, the landscape design can then be adapted to reduce the erosion rate as well as remove the possibility of features such as gullies developing. This is an iterative process which allows a new landscape design to be optimised and assessed at decadal to centennial time scales.

A new generation of soilscape models are now available (Willgoose, 2018). The latest generation of models incorporate both spatially variable hydrology as well as soil material properties (Cohen et al., 2009; Welivitiya et al., 2016). However, while we have these soilscape models, we do not yet have the field data to parameterise these models. There is a near complete lack of data regarding the rates and combination of physical and chemical processes in these new soilscapes. Data is needed for model input so that we can parameterise these models. For example, while we can postulate the weathering process (i.e. chemical and or physical) we have little field data on this. What we have now is largely limited to theoretical understandings and lab experiments (Wells et al., 2006, 2008), though field testing is currently underway. In many ways the soilscape models are more advanced than the field data required for their parameterisation.

Ideally, once a geomorphic design has been developed it can be assessed using a soil erosion model or a LEM, so that an optimised design can be achieved. The design can be input as a stand-alone structure or more importantly, it can be examined as part of a catchment wide assessment – therefore examining how it integrates with the surrounding natural landscape (i.e. Hancock et al., 2006, 2008). This approach will highlight specific design issues as well as successful (or otherwise) linkages with the surrounding catchment.

It should be recognised that LEMs do not operate for all situations. High slope, high rainfall or a combination of the two are problematic. The reason being the hydrology and sediment transport models may not have been developed for such extreme environments and numerical instabilities may result (i.e. the tropics where rainfall can be 10,000 mm/yr). Other situations are dispersive soils where tunnelling occurs. No model presently available can predict tunnel erosion. Another point is that the models are complex and non-trivial to calibrate and use. They need to be used with considerable preparation, thought and result evaluation.

7. Geomorphic rehabilitation in the framework of ecological restoration

Mining affects all components of ecosystems (Nicolau, 2003a). This entails that, after mining, it is usually impossible to restore the pre-disturbance ecosystem, once there are radical changes to almost every component of the landscape, and leaving persistent non-natural landscape features, such as final voids or highwalls (Doley and Audet, 2013). These authors propose, therefore, that for profoundly disturbed sites, it is not practicable to aim for the restoration of pre-disturbance or historical reference or ecosystems (as defined by Balaguer et al., 2014;

McDonald et al., 2016).

Indeed, mining is perhaps one of the few truly human activities where 'irreversible' ecological thresholds (Aronson et al., 1993) are very often crossed. Doley and Audet (2013), have accurately characterized how the nature and extent of environmental disturbance from mining commonly entails completely new challenges. Regarding the abiotic system, it is almost always drastically altered either in landforms (quarries) or lithology and landforms (metallic and coal mining).

We however maintain that by following a geomorphic approach to mine rehabilitation, open-cut mines do not necessarily produce 'novel' ecosystems (in the sense of Hobbs et al., 2006, 2009, 2013), or 'hybrid ecosystems' – "Ecosystem state within which an ecosystem is modified from the historical state by moderate and reversible changes to characteristics involving loss or addition of species (biotic) and/or land use change (abiotic)" (Doley and Audet, 2013, p. 9). Our thesis maintains that, by using geomorphic approaches, mine rehabilitation can approach the principles of ecological restoration.

When only landforms are modified, as it happens in hard-rock quarries, new 'natural landscapes' can be formed, creating totally new landforms for a quarried site (rather than the modification of existing ones). In short, from a flat area of hard-rock (limestone, granite…) we can produce different types of valleys (e.g. canyons, glaciated valleys) for the same setting (as illustrated by the examples at Figs. 11 and 12).

When the mining transformation implies also a change in lithology (i.e. breaking consolidated rocks), this then makes it impossible to reinstate the pre-disturbance lithology conditions, since we do not have any available tool that can reproduce the rock forming geologic processes (e.g. diagenesis or metamorphism). However, non-consolidated waste dumps have similar properties to surficial deposits (e.g. regolith, alluvium, colluvium, glacial tills…). Therefore, replicating landforms similar to those (Quaternary) surficial deposits (alluvial terraces, piedmont colluvium, moraines), given the condition that the analogue landscapes are in a steady state equilibrium is possible. This fact introduces a new perspective in the ecological restoration of mined lands, where the on-site historical ecosystem developed on pre-disturbance landforms on consolidated rocks cannot be reinstated, but in turn, at least theoretically, an off-site historical reference ecosystem typical of nearby surficial deposits can be re-established. Fig. 10 illustrates typical reference landscapes and landforms that are used in fluvial geomorphic rehabilitation. This process aims not to 'recreate' the past—something clearly impossible— but rather to re-establish the historical trajectory of an impaired ecosystem so that it may continue its evolution in response to future conditions (Clewell and Aronson, 2013). Those landforms may be similar to what Doley and Audet (2013) refer as 'novel landforms', only if the 'novel' concept applies to that location, it is to say, "final landforms aligned with the broader bioregional ecosystems". Successful mine rehabilitation depends on understanding the changes in lithology and landforms that the mine imposes.

8. How does climate influence geomorphic landform design and modelling?

Is a geomorphic approach for land restoration more appropriate for some specific climates (e.g. Mediterranean, tropical) is a common question. This is equivalent to enquiring whether ecological restoration is only appropriate for some specific climates. Geomorphic landform design is a generic approach, within ecological restoration. Both approaches are neither defined by the tools they use, nor by the climatic, physiographic or biome zones in which they intervene. Directly, geomorphic principles in land restoration can be used at any Earth's ice free land surface, because such approach only involves understanding the local surface processes and landforms, and trying to handle and manage them (Toy and Chuse, 2005).

Here we focus on a fluvial geomorphic approach (in general) and on the GeoFluv method (specifically). Two important clarifications, regarding climate, are appropriate

Fig. 10. Most common reference landforms and landscapes, developed on unconsolidated materials, for fluvial geomorphic mine restoration. Upper, zig-zag channel on regolith, Puerto Libertador, Colombia. Middle, ephemeral channel on colluvial foothills. Lower, alluvial terraces near La Plata, New Mexico (photo courtesy of Nicholas Bugosh).

- Climate makes a direct influence on the landform properties of the stable analogues that are used to get design inputs (e.g. drainage density, distance from ridgeline to channel's head, or bankfull or floodprone fluvial channels sections). The influence of climate in geomorphic landform design is considered by using such local landform and landscape inputs.
- The GeoFluv method was actually developed in the highly erosive environments of New Mexico, United States, to address mine rehabilitation landform instability by using traditional landform design, and has demonstrated to be successful (Bugosh and Epp, 2019). Its use in other climates include: tropical (Bugosh et al., 2016), Mediterranean (Zapico et al., 2018) or sub-Artic (Baida, 2019).

LEMs are well equipped to assess the impact of changing climate on landform behaviour. The models all have spatially variable rainfall and spatially distributed hydrology capability and can input temporally variable rainfall both from an existing rainfall data set (i.e. a pluviograph) or employ synthetic rainfall data. If climate change scenarios are known with associated rainfall change, then this can be employed. Hancock et al. (2016c, 2017) developed a climate analogue methodology for developing rainfall scenarios under climate change for northern Australia. They demonstrated the effect of this potential rainfall change on a proposed post-mining landscape with a focus on soil erosion and gullying. The method can be easily adapted for other sites globally.

9. Examples of geomorphic rehabilitation

Some examples from quarries in Spain can illustrate how geomorphic rehabilitation is employed. The typical situation of quarries is that most of the extracted material is profitable and leaves the site. Consequently:

- Large pits or voids, with characteristic benched highwalls and platforms outcropping fresh (unweathered) bedrock remain and,
- A small proportion of debris waste rock residuum remains.

From a geomorphic approach the question is: what geomorphologically functional and visually-integrated landforms and landscapes can be designed and built? The answer is:

- Natural limestone/slate cliffs, respectively, mimicking natural ones surrounding the quarries (as described by Gagen and Gunn, 1988; Gunn et al., 1992; Génie Géologique, 2020).
- Colluvial slopes with a drainage network of colluvial channels (as typified by Montgomery and Buffington, 1997), at the foothill of the highwall/cliffs, transitioning towards alluvial channels and rounded hills at the centre of the platforms. These landforms would be designed with the GeoFluv method, through the commercially available software Natural Regrade. The reference sites for the cliffs and colluvial landforms are found at mountain ranges surrounding the quarries. Alluvial channels are based on Rosgen (1994).

Fig. 11 exemplifies the final geomorphic-based ecological restoration design for the slate quarry example, showing the different proposed habitats to be built from the landforms. The rock cliffs and talus scree reproduce equivalent natural analogues. Thyme *(Thymus zygis)* combined with sparto grass *(Stipa tennacissima)* is the proposed habitat for gentle slopes standing on colluvium landforms. Finally, thorny shrubs *(Rubus ulmifolius, Rosa canina, Crataegus monogyna)* are prescribed for valley bottoms reproducing alluvial landforms. The wetland has no reference equivalent in the area but intends to be a natural feature needed for an endorheic void. A rehabilitation solution based on traditional linear landforms at this site was initially rejected by the environmental regulators, because the project is located in a highly ecological sensitive area (habitat of the endangered Iberian Imperial Eagle), but was approved with this geomorphic-based design, because it was considered to be compatible with the highly ecologically sensitive area. This example is described at Zapico et al. (2011).

Fig. 12 includes another example of geomorphic rehabilitation in Spain, this time representing not only simple landforms as analogues, but also a whole (volcanic) landscape. Thus, what formerly was a volcanic hill but is now a quarry, becomes a depression on the top of a mountain, underlain with volcanic rocks. In nature, the analogues of circular depressions on top of hills or mountains underlain by volcanic rocks are 'calderas': cauldron-like hollows that forms shortly after the emptying of a magma chamber/reservoir in a volcanic eruption. Therefore, although there are no such volcanic features in the surroundings, it was assessed that a caldera was the closest natural analogue that could be replicated.

10. Landscape restoration – can it be done?

Humans have been disturbing landscapes for millennia to obtain resources to improve living standards. Agriculture, with its removal of vegetation (particularly forest), then the tillage of soil disturbs landscapes at a far greater scale than that of all mining. Soil loss, loss off biodiversity, changes in water quality, both surface and subsurface are a result of agriculture.

Cities also disturb landscapes at a vast scale. It can be argued that cities and their development disturb landscapes at a far greater scale than mining. The effects are immediate and ongoing to the landscape. Roads, housing, commercial buildings and the necessary services (water, gas, electricity, and sewer) are constructed and remain permanent. This human development of the landscape and imposition of complete human management is

1. Largely accepted by the human community
2. Supports the quality of life we enjoy and have come to expect
3. Will be ongoing as rural areas depopulate and humans move to cities and
4. Requires resources from mining for its ongoing support.

10.1. Community acceptance

A conversation with a long-term mining company employee who is an expert in rehabilitation stated that 'mining is a temporary land use' and that it would last '20–30 years' and then 'the landscape can be used again'. This is a noble goal. Is the idea of resource extraction and continual land use any different to agriculture? In many parts of the

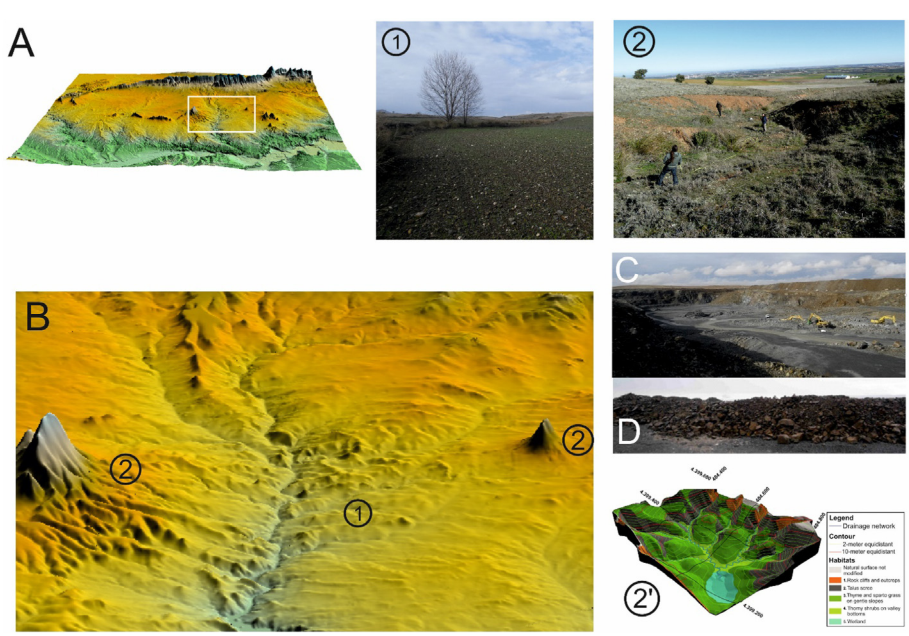

Fig. 11. Example of geomorphic-based ecological restoration of a slate quarry in the Toledo Province. A) Toledo mountain range and piedmont with scattered hills. B) Detail of the piedmont with two hills. 1) Flat surface developed on slate bedrock, 2) Colluvial slate deposits (debris) at the foot of the piedmont hills with a drainage network (colluvial channels). 1 and 2 support thin soils cultivated or grazed, from transformation of holm oak forests (historical reference or ecosystem). C) Open pit of the quarry. D) Mine waste rock (slate debris). 2′ shows a geomorphic landform design that replicates the colluvial foothill with channels (geomorphic analogue). This example demonstrates how the original (pre-disturbance) abiotic conditions of 1 cannot be achieved in mine rehabilitation, once slate has been broken apart in debris. However, these debris are similar to those which support the soils and vegetation at the foothills, and therefore, those landforms can be replicated, as a starting point for the ecological restoration of the site. If the holm oak (historical reference or ecosystem) could be restored, which is doubtful, it would have the abiotic and biotic characteristics that it would have had in 2, but not in 1.

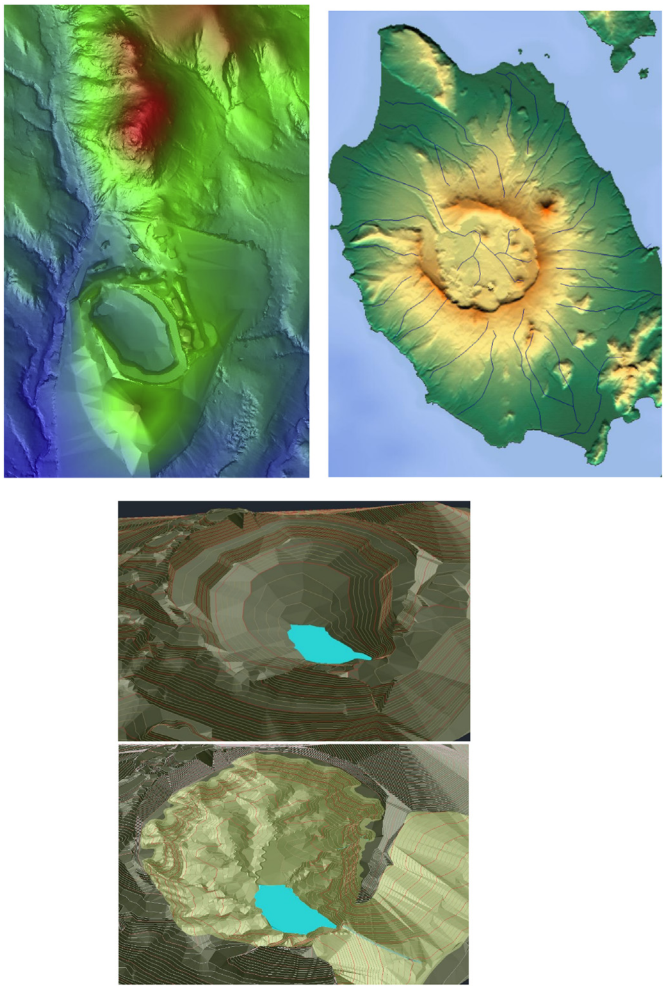

Fig. 12. Upper left, Digital Elevation Model of an andesite (volcanic rock) quarry in Central Spain (Alpedroches); Upper right, Digital Elevation Model of a volcanic caldera (Mount Okmok, https://en.wikipedia.org/wiki/Mount_Okmok). Although the sixe of this caldera has no possible comparison with the Alpedroches quarry, it serves for illustrating a natural open depression developed on volcanic rocks, with a fluvial drainage network at its interior, concept that has been used as an inspirational analogue for geomorphic restoration. Conventional exploitation plan for the quarry (centre top). Geomorphic design that tries to replicate an open volcanic caldera (centre bottom). The bottom of the depression has been designed with GeoFluv-Natural Regrade, suggesting the construction of a drainage network with waste rock dumps. The benches of the highwall are proposed to be regraded replicating natural cliffs, as it would occur at the walls of the caldera.

world, agriculture has been sustainably conducted for many thousands of years. Therefore, new landform rehabilitation strategies need to be adopted in order to maximize post-mine land uses.

Can a rehabilitated post-mining landform ever be the same ecological system such as that pre-mining? Put another way, can a post-mining landscape ever ecologically match that of the pre-mining undisturbed landscape system? The answer is – not likely. The community may need to accept that a post-mining landscape system can never be the same as that pre-mining. But still, it can be a fully functional landscape, by following geomorphic approaches, as described.

The new landscape will likely sit above the pre-existing surface and surrounds and be constructed of a mix of new materials with in some cases a drape of topsoil placed to aid plant establishment. Therefore, it is unlikely that the flora and fauna on a post-mining landscape system will fully match that of its surrounds. The erosion rate, particularly in the initial years is also likely to be higher than that of the surrounding undisturbed system due to the increased slope angle and lengths and initial absence of vegetation.

The community may need to accept that mining will change the landscape forever. There is a need for the community to understand this. However, there is a real need for the industry to continually improve its practices. There is a further need for research to understand how to guarantee the restoration of these landscape systems. At present we can only surmise what the best methods are. Despite that, new mines are often approved with only vague rehabilitation plans and strategy.

10.2. The way forward

The location, landscape and resource grade, surrounding waste/uneconomic material and its volume will be unique to each site. The volume of material amenable to plant growth together with material non-amenable for plant growth will all be different. Each site needs careful planning as well as its own research and trials of rehabilitation methods. These will likely occur after mine commencement so cannot be part of the initial project approval process.

On all modern mine sites landscape rehabilitation is carried out either during mining or at the end of mining. This may involve staff employed at the site or outside contractors managed by the mine employees. As is the nature of the problem, any rehabilitation project will take many seasons to years to even hint at success or otherwise. Some mines will be operating for decades. It is typical for many mine sites for these multi-year projects for the staff member starting the project to leave the business unit or move to another part of the business. In many cases the knowledge regarding the project is lost when the employee leaves.

The authors have seen many instances or been involved in projects where the outside contractor has more knowledge and data than that of the mine environment staff. Therefore important and expensive in-house knowledge can be easily lost. In many cases the rehabilitation project falls to an incoming junior staff member who has to learn and repeat all the mistakes all over again.

There is a need at each mine site to have a formal process of record keeping for rehabilitation programs. This will not only benefit the mine but also provide over time a robust database for other sites. Knowledge of both what works and even more importantly – what does not work – is vital. This record keeping is important not just for each site but for the industry as a whole. Communication of this knowledge will greatly improve this process. Given the importance of developing sustainable landscape systems there may also be a need for rehabilitation approaches, success and failures to be collated in a central data base. This would allow for important information to be available locally, national and internationally and would enhance rehabilitation success.

A big question is – what is the soilscape and ecological trajectory (Tongway and Hindley, 2003, 2004; Willgoose, 2018)? The initial revegetation employed may set the landscape onto very different ecological trajectory to that of the pre-mining and surrounding landscape. The hillslope materials and resultant soils and hydrology will have a different chemistry and soil water holding properties. Vegetation establishment can be both successful and a failure depending on rainfall and climate. Considerable research is needed to qualitatively and quantitatively understand what soilscape path we are following and what can be done to ensure ecological sustainability and integration (Tongway and Hindley, 2003, 2004; Willgoose, 2018).

Further, the mining rehabilitation community needs to think at the catchment scale and consider

- How a landscape will move to maturity when it is constructed of unconsolidated materials.
- Can a mature landscape be built at the beginning with fresh unconsolidated materials, where this fresh material may itself change with time?

- Stand-alone WRDs are not part of a recognised catchment structure, whereas the most common organization of the pre-mined land was in catchments.
- In many cases earthworks costs dominate the rehabilitation costs and can be a major sunk cost for miners when soil and vegetation establishment commences.

Mine planners are exceptionally good at building low cost linear landscapes that are financially cost-effective in the short-term for the mining company. However, they are likely to be more expensive for the community at decadal and centennial time scales. The work of Bradshaw (1987) provides a fundamental insight and guide as to what we are expressing here. In its original formulation it only addresses the 'abiotic' restoration issue and takes a point based understanding, rather than incorporate geomorphology, and we suggest to be recast in this light.

11. Conclusion

If during and after mining is complete, and if the correct ecological building blocks are established, an ecosystem may be able to be placed on a soilscape restoration trajectory. However, what is lacking in this approach is that rehabilitation firstly has to take place with the concept of the hillslope and catchment being a fundamental landscape (geomorphic) unit and that ecological restoration will be driven by the water, sediment and nutrient movement.

There may be multiple pathways with each having a different outcome. This again begs the question of how to ensure a certain soilscape direction is taken - or even if we are able to force a soilscape down a certain path. It may be we cannot ensure any single path and that the best approach is to use the best design principles that we have to establish the building blocks for a self-sustaining and integrated new landscape based on the catchment as the fundamental geomorphic unit.

The use of geomorphic design and assessment using landscape evolution models alone is no guarantee of success. They are concepts and tools which need to employed using an integrative understanding of geomorphology and soils together with ecology and biology. The new landscape is also constrained by surrounding land use, legal boundaries and community expectations. A new approach for landscape restoration using this integrative approach will best ensure post-mining landforms become integrated landscape units with an ecological productivity equal to (yet potentially and acceptably different) to that of the pre-mine surface and surrounds. This review paper provides detail on how with expert geomorphic understanding, diagnosis, design and modelling can be incorporated to mine rehabilitation to provide a higher chance of restoration success.

Declaration of competing interest

None.

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