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

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42 **Abstract**

43

44 Mining is essential to the human economy and has been conducted for millennia. In the past  
45 ~60 years, the scale of disturbance created by mining has grown larger in response to economic  
46 demands and technology capacity. However the scale of disturbance from mining is dwarfed  
47 by that of urban expansion and agriculture. Nevertheless, it is well recognised that mine sites  
48 have radically disturbed abiotic and biotic system components that, post-mining need to restore  
49 new land uses and ecosystem goods and services. In many cases, such aims demand a  
50 geomorphic integration with the surrounding undisturbed landscape. Erosional stability based  
51 on geomorphic principles is the first and most important part of the process. Without erosional  
52 stability, vegetation will be difficult to establish and maintain and soil and nutrients will be lost  
53 from the site. In this review we outline this process and methods by which a geomorphic and  
54 integrative landscape can be established. We also examine the issue of establishing a self-  
55 sustaining landscape that is similar to that of the prior undisturbed landscape. Here we argue  
56 that this is not possible in almost all situations, however the development of a new and  
57 ecologically successful, albeit different landscape is. The community needs to accept that  
58 mining, like agriculture, is essential to the modern economy and that a past landscape cannot  
59 be replaced with the same, but a new, functional and productive one can be developed.  
60 However, the ability to do this and ensure long-term ecological sustainability is questionable  
61 for many sites and considerable effort needs to be made to develop the technology to ensure  
62 that this will occur. We outline a way forward, based on geomorphic design and modelling.

63

64

65 **Keywords:** sustainable landscape design; soilscape; landscape evolution modelling; mine  
66 rehabilitation; soil erosion modelling

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68

69 **1 Introduction**

70 Mining provides considerable economic and social benefit to the global human  
71 population. However, mining is an intensely transformative activity where the earth is removed  
72 to extract or exploit a resource (U.S. Dept. of Interior, 1971; Young, 1992; Mossa and James,  
73 2013). Here we focus on open cut mining where the earth's surface is removed to expose the  
74 resource. Open cut mining 'opens up' the landscape to access and extract resources. While  
75 open cut mining has always been practised by humans, pre 1945 it was mostly small scale due  
76 to the lack of technology. The size of the mines and the landscape scale over which it is  
77 conducted is only possible now due to modern technology that allows the earth's surface in  
78 most cases to be firstly broken up with explosives and secondly, this broken up material  
79 removed in a cost effective way by large machinery. The technology and efficiency to access  
80 a resource is continually improving as well as mines and their size becoming large in both  
81 surface area and depth. The scale of the new land transformation (abiotic change) is so large  
82 and new that there are no fully tested rehabilitation solutions for such largescale scenarios  
83 (Hobbs et al., 2006; 2009).

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

93 gravel pits, or mining in different loose sedimentary material, the situation is the opposite, since  
94 the volume of the extracted raw material is either missing in the end, for example, if most of  
95 the rock is beneficial product. In these scenarios, topographical depressions, frequently with  
96 lakes at their bottom, are the post-mining landscape to face.

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

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

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

130

### 131 **1.1 The goal for post-mine landscape reconstruction**

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

- 139 1. The waste rock will be very different to that of the natural surrounds (and of the pre-  
140 mining landscape) (Doley and Audet, 2013). In some cases recovered topsoil is placed  
141 over the waste rock to aid revegetation – but whether it will be waste rock or waste rock  
142 with a topsoil cover, it will be very different to the natural surface (either pre-mine or

143 surroundings of the mine). Therefore different ecological communities and processes  
144 are likely to operate at least in the initial years post-mining (Hobbs et al., 2006).

145 2. The material and landscape is ‘new’ in that it has been created ‘de novo’ (Doley and  
146 Audet, 2013). All materials and hillslope shape are new and there is very little  
147 knowledge as to how the new material will evolve and at what rate. That is, how will  
148 new soil form, at what rate and what will the soil evolve to? For example, waste  
149 materials can have very different pH and chemical composition to that of the pre-mine  
150 surface. Therefore assuming success of a post-mining landscape rehabilitation is not a  
151 short-term consideration. The evolution of the surface in terms of soil development (or  
152 pedogenesis) may take decades or centuries to occur with the flora and fauna evolving  
153 in concert (Cohen et al., 2009).

154 3. How do starting conditions (i.e. surface slope, slope length and materials) and resultant  
155 hydrology and initial vegetation influence landscape trajectory? If one method or  
156 pattern of rehabilitation is undertaken, does this affect the soilscape reconstruction?

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

159 The materials that the new surface is constructed from are very different to that of the  
160 original surface. Physically, the material may be very rocky which may be a very erosionally  
161 stable material but too coarse to hold water and therefore will limit plant growth (Figure 1). In  
162 other scenarios, bedrock or loose sediments outcrop at the bottom of closed pits (Wirth et al.,  
163 2012).

164 In almost all situations, the new exposed materials will have very different physical and  
165 chemical properties and therefore will weather to a different soil to that of the pre-mining and  
166 surrounding landscape surface. This is the case, for example, of shale, schists or different types  
167 of saprolite. Many of these rapidly weathering materials are highly erodible and may contain

168 high levels of salts, which impede vegetation establishment (Figure 2). There is also poor  
169 knowledge about the weathering behaviour of the waste rock and how this will affect the  
170 evolution of the new landscape (Wells et al., 2006; 2008). Nicolau (2003b) reports  
171 investigations by Martin Haigh in which accelerated erosion occurred on initially successful  
172 pasture restored in Welsh coalfields, as a consequence of weathering of waste shale and  
173 formation of an impervious clay layer in the soil at the depth of 30 cm. The goal at sites such  
174 as this is to identify the materials during the extraction process and burying any suboptimal  
175 materials deep within the waste rock dump (WRD) surrounded by inert non-hostile materials.  
176 This encapsulation process ensures that many waste rock dumps are relatively tall. Therefore  
177 at almost all sites the landscape has taller and steeper slopes. The alternative is to have a less  
178 tall landscape with lower slopes – but this increases the new landscape footprint.

179 All mines seek to disturb the smallest footprint possible. Increasing a mine footprint is  
180 something that is usually avoided as the financial bond placed on a mine is usually based on  
181 the amount of area disturbed. Another reasoning is that if there is less disturbed area, then there  
182 will be fewer rehabilitation problems. However, fixing the dump toe limit to some arbitrary  
183 line is not always beneficial, and in some cases better results may be achieved if the toe or  
184 footprint could be expanded. For example, a proposal (approved in 2017) for a geomorphic-  
185 based rehabilitation of a coal mine in Colombia extended the toe disturbance limit of an out-  
186 of-pit waste rock dump slightly, but provided a functional geomorphological integrated  
187 landform that overcomes the problems of the traditional reclamation landforms (Bugosh et al.,  
188 2016; Figure 3). Therefore rehabilitation (McDonald et al., 2016) to another optimally  
189 functional system may be the only possible outcome. But there are situations where increasing  
190 the mine footprint is not possible. This happens where the slopes are steep and the space is  
191 limited. This situation is typical for mines in mountainous areas (Martín-Moreno et al., 2018).

192 Expanding a mine footprint is usually impossible in densely populated areas (i.e. Europe).  
193 Therefore, this discussion is more relevant for regions with low population density.

194

## 195 **1.2 The catchment scale/dimension**

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

205 Many drainage networks of the earth's surface have a control imposed by the geological  
206 structures (e.g. faults, joints, strata). Some natural drainage networks do not have such control  
207 of the bedrock structure. In non-consolidated recent sediments, or homogeneous materials they  
208 usually have a 'dendritic' form (Dunne and Leopold, 1978). In terms of rehabilitation, it should  
209 be understood that most of the pre-mine drainage networks have such geological structure  
210 control, whereas post-mine landscapes on waste rock will tend to develop dendritic networks  
211 (Bugosh, 2004).

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

214

## 215 **1.3 Off-site impacts**

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

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

233

## 234 **2 Sound references sites and geomorphic analogues**

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

241

## 242 **2.1 Current practice**

243 A common practice for new mine landscapes is to construct stand-alone WRDs (Fig. 6;  
244 Orman et al., 2011). They are constructed in different physiographic locations to simple linear  
245 designs (with a number of ‘lifts’ of usually 10 m steps) with maximum economic efficiency.  
246 This efficiency is a monetary cost issue where the dump is usually located close to the pit so  
247 that cost, travel time and distance to transport the waste material is minimised. However, for  
248 the majority of these landscapes they are stand-alone and out of keeping structures with no  
249 geomorphological link, both functionally and visually, to their surrounds. To manage runoff,  
250 control structures such as contour or graded banks and engineered (downdrain) channels are  
251 constructed (Figure 4). There is also little consideration as to how these landscapes will mature  
252 through time.

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

261 Unique landscapes for mines are Tailings Storage Facilities (TSF). These are dams that  
262 contain fine material from the mineral processing and are usually wet, highly erodible and often  
263 contain contaminants. They can be stand-alone structures or accommodated into the natural  
264 landscape (valley fill). However, given their content, they need to be erosionally stable where  
265 the potential risk for dam failures or acid drainage (a common issue) is reduced (Johnson and

266 Hallberg, 2005). Here, the main aim is isolation, rather than an integration with surrounding  
267 landscapes, but this issue is starting to be resolved with promising results (Slingerland et al.,  
268 2019).

269

## 270 **2.2 Functional and non-functional landscapes**

271 There is a danger that anything that deviates from the current linear construction will  
272 be called geomorphic design. For example, trying to imitate surrounding or pre-mine scalloped  
273 landforms is a type of well-intentioned landscaping work, but lacks scientific basis. The authors  
274 have observed this type of design by consultants worldwide, with little holistic and scientific  
275 understanding of hillslope and catchment processes (i.e. geomorphology). Geomorphic  
276 research using natural landscapes can now link hydrology and erosion process to the landforms  
277 and drainage network quantitatively (Willgoose, 2018); for instance, slope gradient with  
278 catchment area (Willgoose et al., 1991a), drainage network geometry (Perera and Willgoose,  
279 1998), spatial distribution of elevation (Willgoose and Hancock, 1998), and spatial distribution  
280 of erosional energy (Ibbitt et al., 1999). These links between catchment processes and  
281 geomorphology suggest fundamental properties of constructed landscapes that need to be  
282 replicated and how they vary between natural and post-mining landforms. Often, looking good  
283 at the beginning will lead to widespread erosion. The most serious consequences of this  
284 approach are that they frequently lead to general instability, with serious liability consequences  
285 for all involved.

286 The authors interpret that this attempt to ‘recreate’ the natural landforms that surround  
287 a particular mine in its rehabilitation process comes from the Approximate Original Contour  
288 (AOC) concept included in the Surface Mining Control and Reclamation Act, SMCRA, 1977  
289 (United States). This law states (p. 114): “*AOC means that surface configuration achieved by*  
290 *backfilling and grading of the mined area so that the reclaimed area, including any terracing*

291 *or access roads, closely resembles the general surface configuration of the land prior to mining*  
292 *and blends into and complements the drainage pattern of the surrounding terrain...”.*  
293 However, it should be noted that much of the science underpinning current work post-dates the  
294 publication of this document.

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

312         It needs to be recognised that the current practice of trying to replicate natural landforms  
313 that have evolved on consolidated rock with the same landscape (but now constructed on  
314 unconsolidated material) seems to have played an important role in the growing influence of  
315 landscaping, as used in landscape architecture. For example, in the text *Landforming*, Shor and

316 Gray (2007) demonstrate landscape architecture has positive outcomes for new urban  
317 developments. The conflict arises when these general approaches of landscaping and  
318 landforming are intended to be applied in large mining areas without geomorphic principles.  
319 This occurs because of a lack of knowledge as to the basic principles that operate (i.e. fluvial  
320 processes) within a catchment and without the knowledge on how the change in physical and  
321 chemical properties affect the potential of rehabilitation of minescapes (Toy and Chuse, 2005).

322

### 323 **3 The development of geomorphic rehabilitation - A brief history**

324 The demand for introducing geomorphic principles in mine rehabilitation developed in  
325 the US, UK and Australia in the late 1970s and early 1980s. The US SMCRA (1977) can be  
326 considered the first text in this regard, asking for the need for complementing the drainage  
327 pattern of the surrounding terrain. It actually introduced a ‘catchment approach’ in mine  
328 rehabilitation — using the drainage basin as the fundamental unit for planning mine  
329 rehabilitation and guaranteeing hydrological connectivity. This approach was explicitly  
330 expressed later by Stiller et al. (1980), who asserted that planning for long-term stability of  
331 reclaimed surface mines meant incorporating drainage networks that would integrate into the  
332 surrounding landscape. A little later (1987) and also in the US, this new discipline had already  
333 its own book, *Geomorphology and Reclamation of Disturbed Lands*, by Toy and Hadley. After  
334 1990, the US scientific literature relating geomorphic reclamation of disturbed lands grew (i.e.,  
335 Toy and Black, 2000; Toy and Chuse, 2005; DePriest et al., 2015; among many others).

336 Furthermore, specific classifications, tools and software were developed in the US for  
337 geomorphic rehabilitation of mined sites. The Rosgen (1994, 1996) morphological  
338 classification of rivers is in itself a geomorphic reconstruction method. This approach has been  
339 widely employed for perennial stream reconstruction in the United States, including mined  
340 sites. The updates and learnings since the implementation of the AOC concept were also the

341 breeding ground for the reclamation method GeoFluv™ — from Geomorphic and Fluvial  
342 (Bugosh, 2000, 2003). GeoFluv (discussed in detail later) is a geomorphic method for land  
343 rehabilitation that is able to reproduce the complexity of natural landforms and drainage  
344 networks within catchments, which become the basic rehabilitation design units. This  
345 technique began to be applied at large coal mines of New Mexico (United States) in 1999.  
346 Natural Regrade is the commercial software (Carlson software, 2019), launched in 2005, that  
347 helps users to efficiently make GeoFluv designs in a CAD format. GeoFluv through Natural  
348 Regrade has been successfully used in the US (Bugosh and Epp, 2019). RIVERMorph (2017)  
349 is a design software based on the principles established by Rosgen (1994, 1996). Today,  
350 Geomorphic Reclamation is officially recognized within the OSMRE Technology  
351 Development and Transfer (TDT) program (<http://www.osmre.gov/programs/TDT.shtm>), and  
352 states as New Mexico have a regulation that considers that a geomorphic approach to  
353 backfilling and grading is the Best Technology Currently Available (BTCA) for stabilizing  
354 coal mine reclamation (NMMM, 2010).

355         Australia pioneered also the geomorphic and catchment approaches to mine  
356 rehabilitation, with the book *Mine Rehabilitation* (Hannan, 1984). These geomorphic  
357 principles were later extensively developed in the handbook *Landform Design for*  
358 *Rehabilitation* (Environment Australia, 1998). In parallel, and mostly due the application of  
359 the Landscape Evolution Model SIBERIA for landform design in mine rehabilitation, Australia  
360 developed the most extensive set of both scientific (papers and books) and industry handbooks  
361 dealing with landform design in mine rehabilitation. Benchmark papers appeared in the mid-  
362 1990s (Evans and Riley, 1994; Riley, 1995a, b; or Willgoose and Riley, 1998, among others).  
363 This literature body was largely extended from the 2000s up to now (Hancock et al., 2003;  
364 Hancock and Willgoose, 2018).

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

372 In Europe, specific examples and publications on Geomorphic Mine Rehabilitation  
373 come mostly from the United Kingdom, Spain and France. In the United Kingdom, a method  
374 for replicating natural landforms at hard rock quarry faces was developed in the late 1970s  
375 (Humphries, 1977, 1979), and continued for the same mine setting with work of the Limestone  
376 Research Group of the Manchester Polytechnic (Gagen and Gunn, 1988; Gunn et al., 1992). In  
377 Spain, scientific applications and literature in this field started to appear at the end of the 1990s  
378 and continued since then (Martín Duque et al., 1998; Nicolau, 2003a; Martín Duque et al.,  
379 2010, Zapico et al., 2018). The main application of Geomorphic Mine Rehabilitation in Europe  
380 is in kaolin and silica sand mines and limestone and clay quarries in Spain. It has been  
381 recognized at the European level by means of recognising Geomorphic Reclamation as one of  
382 the Best Available Techniques for the Management of Waste from the Extractive Industries  
383 (JRC, 2018). Finally, in France, the Talus Royal method has been successfully applied at rock  
384 roadcuts in France (Génie Géologique, 2020) and is starting to be applied in rock highwalls at  
385 quarries. This method is convergent with the one in the United Kingdom and attempts to  
386 compress time by designing and building the ‘natural’ rock cliffs or scree (talus) slopes that  
387 would tend to form and evolve with time, through falls and slides that occur preferentially on  
388 weathered or fractured rocks. Equivalent natural cliffs or rock slopes are used as analogues. In

389 Table 1 we have compiled our own synthesis of geomorphic landform design methods, along  
390 with soil erosion and landscape evolution models, and related software, for mine rehabilitation.

391

#### 392 **4 Geomorphic principles and analogues**

393 Open cut mining removes topsoil, breaks underlying horizonisation and geological  
394 structure eliminating any organisation that has developed over geological time. With that  
395 geological age and structure comes soils which have coevolved with vegetation, climate and  
396 biology (Butler, 2006).

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

404 Natural landforms and landscapes follow universal geomorphic principles. Outside a  
405 few environments (such as high mountains and deserts or sand deserts), or specific hard-rock  
406 landforms (such as cliffs), most of the Earth's ice-free land surface is organized in drainage  
407 basins, which have been shaped mostly by fluvial and hillslope processes. They are comprised  
408 of streams, hillslopes and divides, all of which interact with one other. Stiller et al. (1980) have  
409 claimed that the drainage basin should be used as the fundamental planning unit for mine  
410 rehabilitation. The referred natural hillslopes are never linear with constant gradient. On the  
411 contrary, they universally have convex profiles at the top of a slope and change to concave as  
412 the hillslope length increases (Environmental Australia, 1998). Stream channels rarely have  
413 planar longitudinal profiles, but become progressively steeper as one moves upstream, and the

414 width and depth having evolved to match the upslope catchment area. When following  
415 geomorphic principles in mine rehabilitation, stream longitudinal profile gradients should be  
416 progressively steeper upstream and flatter downstream, mirroring stable natural channels  
417 (Environment Australia, 1998). Also, the natural channel geometry is based on bankfull  
418 discharge, and have different width-to-depth ratios and sinuosity depending of the stream types  
419 (Rosgen, 1994, 1996). The geometry of natural meandering channels is not random. It follows  
420 moderately understood mathematical relationships between bankfull width, radius of curvature  
421 of meanders, meander belt widths and meander wavelengths (Leopold and Wolman, 1960;  
422 Williams, 1986). The use of such fluvial geomorphic principles in mine rehabilitation has been  
423 and is common in the United States and Canada. Sawatsky and Beckstead (1996) offer also  
424 universal fluvial geomorphic principles that have been successfully used in the Canadian oil  
425 sands restoration: (a) floodplains and meandering channels significantly reduce flow velocities;  
426 (b) instead of rigid bed and banks, designed ‘natural’ streams have a mobile bed composed of  
427 natural armour, which moves in response to flood events; (c) despite the high rates of changes  
428 that may occur, replication of natural channels is more sustainable, and far superior to most  
429 rigid-engineered drainage systems. The GeoFluv method (Bugosh, 2000, 2003; Bugosh and  
430 Epp, 2019), gathers and synthetizes most of these fluvial geomorphic principles, to be used in  
431 any land reclamation involving earth movements. The method complements them with other  
432 quantitative morphological parameters that define natural drainage basins (Horton, 1945), such  
433 as drainage density, length of overland flow (distance from ridgeline to channel’s head), or  
434 scalloped hillslope topography at upland areas, among others.

435         The use of natural analogues in mine rehabilitation results in a significantly higher  
436 landform and habitat diversity (complex convex-concave hillslopes, with different aspect,  
437 cliffs, valleys, wetlands) compared to conventional landform design, which results in very

438 homogeneous topography. Therefore, the use of geomorphic landform design has demonstrated  
439 to have advantages from a biodiversity point of view (Fleisher and Hufford, 2020).

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

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

454 At some sites geomorphological analogues have been sought. The ERA Ranger mine  
455 in the Northern Territory, Australia has been the focus of intense environmental scrutiny due  
456 to its location surrounded by the World Heritage listed Kakadu National Park. The site has two  
457 open pits which will be infilled and a tailings dam which will be removed. The mine has  
458 operated since the 1980s and plans for rehabilitation began at this time.

459 Here a potential analogue site, Tin Camp Creek, was found which is geologically and  
460 geochemically similar to that of the Ranger mine waste (Riley and Rich, 1998) (Figure 8). This  
461 site has been extensively examined as a geomorphic analogue where its erosion rate, hydrology

462 and long-term evolution has been a focus (Hancock et al., 2002; Moliere et al., 2002; Hancock  
463 and Evans, 2010; Hancock and Lowry, 2015; Hancock et al., 2016a, b, c).

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

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

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

482 (2) For consolidated bedrock at highwalls and benched terraces, natural cliffs  
483 developed over thousands of years on the same type of rocks, gradients, aspects and  
484 climate provide analogues. This approach is mostly used for replicating natural  
485 landforms at hard rock quarry faces (Gagen and Gunn, 1988; Gunn et al., 1992) and  
486 by the Talus Royal method (Génie Géologique, 2019).

487

## 488 **5 Vegetation and landscape evolution**

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

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

512 For many sites (such as the Hunter Valley) the potential is there for any reconstructed  
513 landscape to have a higher biological productivity post-mining to that of the pre-mining  
514 landscape as any clay horizons and bedrock have been removed with the emplaced waste rock  
515 providing what is effectively an infinite soil depth. Theoretically, this infinite soil depth can  
516 capture all rainfall allowing maximum soil water storage. The ability to capture and hold water  
517 allows an optimal vegetation system to evolve. However, this assumes that the material can  
518 capture and hold water as well as having no physical or chemical constraints (Figures 1 and 2).  
519

## 520 **6 Pre and post-landscape design and assessment – models and modelling**

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

527

### 528 **6.1 Landscape evolution models**

529 There are a number of models and modelling approaches that can be employed for post-  
530 mining landscape assessment with a compilation in Table 1. The most widely used model is  
531 the Universal Soil Loss Equation (USLE) and its derivatives such as the Revised Universal soil  
532 Loss Equation (RUSLE). It has been used globally for many decades and has proven to be a  
533 useful and reliable tool (Wischmeier and Smith, 1978; Flanagan and Livingston, 1995). Given  
534 its global use, model parameters and data sets can be easily found or more reliable parameters  
535 can be determined from site specific data. However, a disadvantage is that the RUSLE only  
536 models erosion, not deposition, and only provides average erosion. A hillslope is assumed to

537 be uniform and does indicate where erosion occurs on the hillslope. Other models such as the  
538 Water Erosion Prediction Program (WEPP) include a climate function, vegetation and plant  
539 growth functions and hillslopes can be mathematically linked to form multiple hillslopes  
540 (Flanagan and Livingston, 1995). However, these models neither evolve the landform nor  
541 properly consider gully erosion, and it happens that, in post-mining landscapes, the majority of  
542 erosion occurs by gully erosion caused by fluvial erosion (Hancock et al., 2000; 2013), in a process  
543 of redevelopment of a drainage network.

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

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

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

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

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

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

585

586 **7 Geomorphic rehabilitation in the framework of ecological restoration**

587 Mining affects all components of ecosystems (Nicolau, 2003a). This entails that, after  
588 mining, it is usually impossible to restore the pre-disturbance ecosystem, once there are radical  
589 changes to almost every component of the landscape, and leaving persistent non-natural  
590 landscape features, such as final voids or highwalls (Doley and Audet, 2013). These authors  
591 propose, therefore, that for profoundly disturbed sites, it is not practicable to aim for the  
592 restoration of pre-disturbance or historical reference or ecosystems (as defined by Balaguer et  
593 al., 2014; McDonald et al., 2016).

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

600 We however maintain that by following a geomorphic approach to mine rehabilitation,  
601 open-cut mines do not necessarily produce ‘novel’ ecosystems (in the sense of Hobbs et al.,  
602 2006, 2009, 2013), or ‘hybrid ecosystems’ – “Ecosystem state within which an ecosystem is  
603 modified from the historical state by moderate and reversible changes to characteristics  
604 involving loss or addition of species (biotic) and/or land use change (abiotic)” (Doley and  
605 Audet, 2013, p. 9). Our thesis maintains that, by using geomorphic approaches, mine  
606 rehabilitation can approach the principles of ecological restoration.

607 When only landforms are modified, as it happens in hard-rock quarries, new ‘natural  
608 landscapes’ can be formed, creating totally new landforms for a quarried site (rather than the  
609 modification of existing ones). In short, from a flat area of hard-rock (limestone, granite...) we

610 can produce different types of valleys (e.g. canyons, glaciated valleys) for the same setting (as  
611 illustrated by the examples at Figures 11 and 12).

612         When the mining transformation implies also a change in lithology (i.e. breaking  
613 consolidated rocks), this then makes it impossible to reinstate the pre-disturbance lithology  
614 conditions, since we do not have any available tool that can reproduce the rock forming  
615 geologic processes (e.g. diagenesis or metamorphism). However, non-consolidated waste  
616 dumps have similar properties to surficial deposits (e.g. regolith, alluvium, colluvium, glacial  
617 tills...). Therefore, replicating landforms similar to those (Quaternary) surficial deposits  
618 (alluvial terraces, piedmont colluvium, moraines), given the condition that the analogue  
619 landscapes are in a steady state equilibrium is possible. This fact introduces a new perspective  
620 in the ecological restoration of mined lands, where the on-site historical ecosystem developed  
621 on pre-disturbance landforms on consolidated rocks cannot be reinstated, but in turn, at least  
622 theoretically, an off-site historical reference ecosystem typical of nearby surficial deposits can  
623 be re-established. Figure 10 illustrates typical reference landscapes and landforms that are used  
624 in fluvial geomorphic rehabilitation. This process aims not to ‘recreate’ the past—something  
625 clearly impossible— but rather to re-establish the historical trajectory of an impaired ecosystem  
626 so that it may continue its evolution in response to future conditions (Clewell and Aronson,  
627 2013). Those landforms may be similar to what Doley and Audet (2013) refer as ‘novel  
628 landforms’, only if the ‘novel’ concept applies to that location, it is to say, “final landforms  
629 aligned with the broader bioregional ecosystems”. Successful mine rehabilitation depends on  
630 understanding the changes in lithology and landforms that the mine imposes.

631

## 632 **8         How does climate influence geomorphic landform design and modelling?**

633         If a geomorphic approach for land restoration more appropriate for some specific  
634 climates (e.g. Mediterranean, tropical) is a common question. This is equivalent to enquiring

635 whether ecological restoration is only appropriate for some specific climates. Geomorphic  
636 landform design is a generic approach, within ecological restoration. Both approaches are  
637 neither defined by the tools they use, nor by the climatic, physiographic or biome zones in  
638 which they intervene. Directly, geomorphic principles in land restoration can be used at any  
639 Earth's ice free land surface, because such approach only involves understanding the local  
640 surface processes and landforms, and trying to handle and manage them (Toy and Chuse,  
641 2005).

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

- 644 • Climate makes a direct influence on the landform properties of the stable analogues that  
645 are used to get design inputs (e.g. drainage density, distance from ridgeline to channel's  
646 head, or bankfull or floodprone fluvial channels sections). The influence of climate in  
647 geomorphic landform design is considered by using such local landform and landscape  
648 inputs.
- 649 • The GeoFluv method was actually developed in the highly erosive environments of  
650 New Mexico, United States, to address mine rehabilitation landform instability by using  
651 traditional landform design, and has demonstrated to be successful (Bugosh and Epp,  
652 2019). Its use in other climates include: tropical (Bugosh et al., 2016), Mediterranean  
653 (Zapico et al., 2018) or sub-Artic (Baida, 2019).

654 LEMs are well equipped to assess the impact of changing climate on landform  
655 behaviour. The models all have spatially variable rainfall and spatially distributed hydrology  
656 capability and can input temporally variable rainfall both from an existing rainfall data set (i.e.  
657 a pluviograph) or employ synthetic rainfall data. If climate change scenarios are known with  
658 associated rainfall change, then this can be employed. Hancock et al. (2016c; 2017) developed  
659 a climate analogue methodology for developing rainfall scenarios under climate change for

660 northern Australia. They demonstrated the effect of this potential rainfall change on a proposed  
661 post-mining landscape with a focus on soil erosion and gullyng. The method can be easily  
662 adapted for other sites globally.

663

## 664 **9 Examples of geomorphic rehabilitation**

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

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

671

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

- 674 • Natural limestone/slate cliffs, respectively, mimicking natural ones surrounding the  
675 quarries (as described by Gagen and Gunn, 1988; Gunn et al., 1992; Génie Géologique,  
676 2020).
- 677 • Colluvial slopes with a drainage network of colluvial channels (as typified by  
678 Montgomery and Buffington, 1997), at the foothill of the highwall/cliffs, transitioning  
679 towards alluvial channels and rounded hills at the centre of the platforms. These  
680 landforms would be designed with the GeoFluv method, through the commercially  
681 available software Natural Regrade. The reference sites for the cliffs and colluvial  
682 landforms are found at mountain ranges surrounding the quarries. Alluvial channels are  
683 based on Rosgen (1994).

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

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

704

## 705 **10 Landscape restoration – can it be done?**

706 Humans have been disturbing landscapes for millennia to obtain resources to improve  
707 living standards. Agriculture, with its removal of vegetation (particularly forest), then the  
708 tillage of soil disturbs landscapes at a far greater scale than that of all mining. Soil loss, loss

709 off biodiversity, changes in water quality, both surface and subsurface are a result of  
710 agriculture.

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

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

720

## 721 **10.1 Community acceptance**

722 A conversation with a long-term mining company employee who is an expert in  
723 rehabilitation stated that ‘mining is a temporary land use’ and that it would last ‘20-30 years’  
724 and then ‘the landscape can be used again’. This is a noble goal. Is the idea of resource  
725 extraction and continual land use any different to agriculture? In many parts of the world,  
726 agriculture has been sustainably conducted for many thousands of years. Therefore, new  
727 landform rehabilitation strategies need to be adopted in order to maximize post-mine land uses.

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

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

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

746

## 747 **10.2 The way forward**

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

754           On all modern mine sites landscape rehabilitation is carried out either during mining or  
755 at the end of mining. This may involve staff employed at the site or outside contractors  
756 managed by the mine employees. As is the nature of the problem, any rehabilitation project  
757 will take many seasons to years to even hint at success or otherwise. Some mines will be  
758 operating for decades. It is typical for many mine sites for these multi-year projects for the staff

759 member starting the project to leave the business unit or move to another part of the business.  
760 In many cases the knowledge regarding the project is lost when the employee leaves.

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

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

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

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

786 • How a landscape will move to maturity when it is constructed of unconsolidated  
787 materials.

788 • Can a mature landscape be built at the beginning with fresh unconsolidated  
789 materials, where this fresh material may itself change with time?

790 • Stand-alone WRDs are not part of a recognised catchment structure, whereas the  
791 most common organization of the pre-mined land was in catchments.

792 • In many cases earthworks costs dominate the rehabilitation costs and can be a major  
793 sunk cost for miners when soil and vegetation establishment commences.

794

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

802

## 803 **11 Conclusion**

804 If during and after mining is complete, and if the correct ecological building blocks are  
805 established, an ecosystem may be able to be placed on a soilscape restoration trajectory.

806 However, what is lacking in this approach is that rehabilitation firstly has to take place with  
807 the concept of the hillslope and catchment being a fundamental landscape (geomorphic) unit

808 and that ecological restoration will be driven by the water, sediment and nutrient movement.

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

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

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**Figure 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.

**Figure 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](https://en.wikipedia.org/wiki/Mount_Okmok)). Although the since 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. Lower left, conventional exploitation plan for the quarry. Lower right, geomorphic design that tries to replicate an open volcanic caldera. 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.

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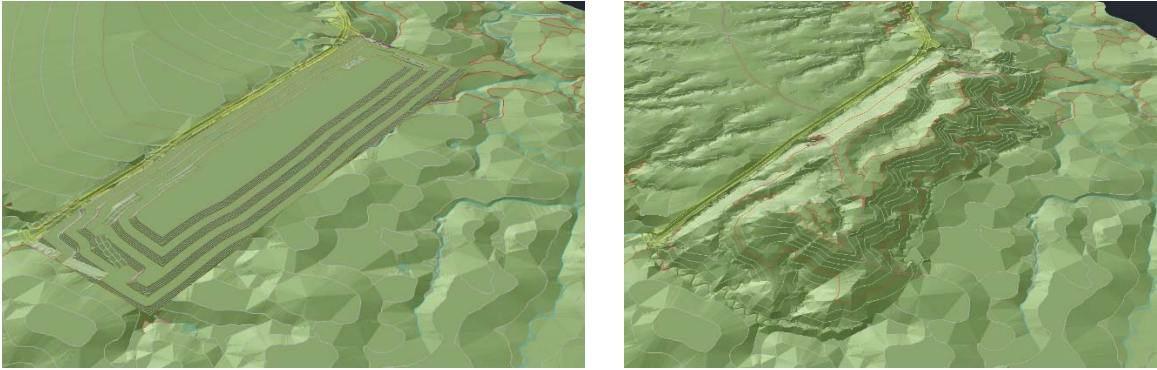
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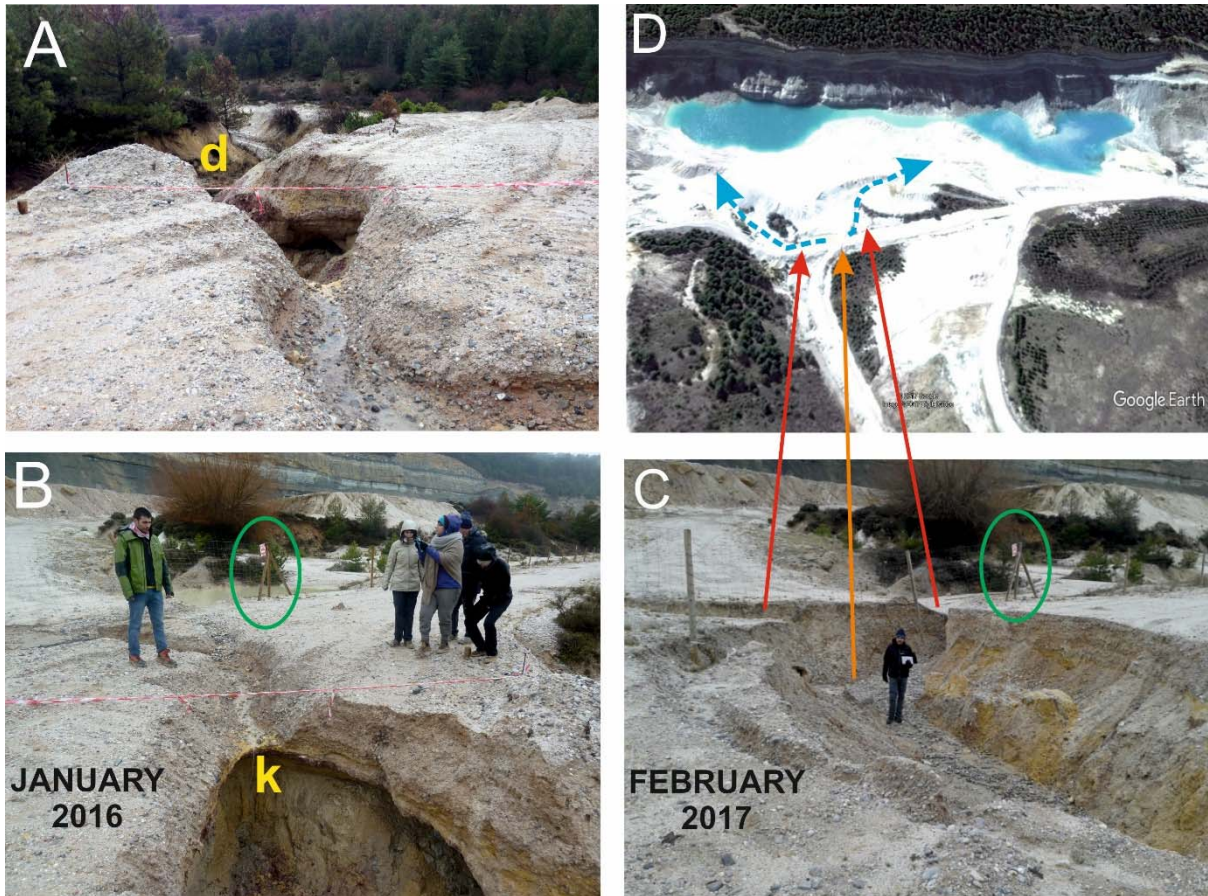
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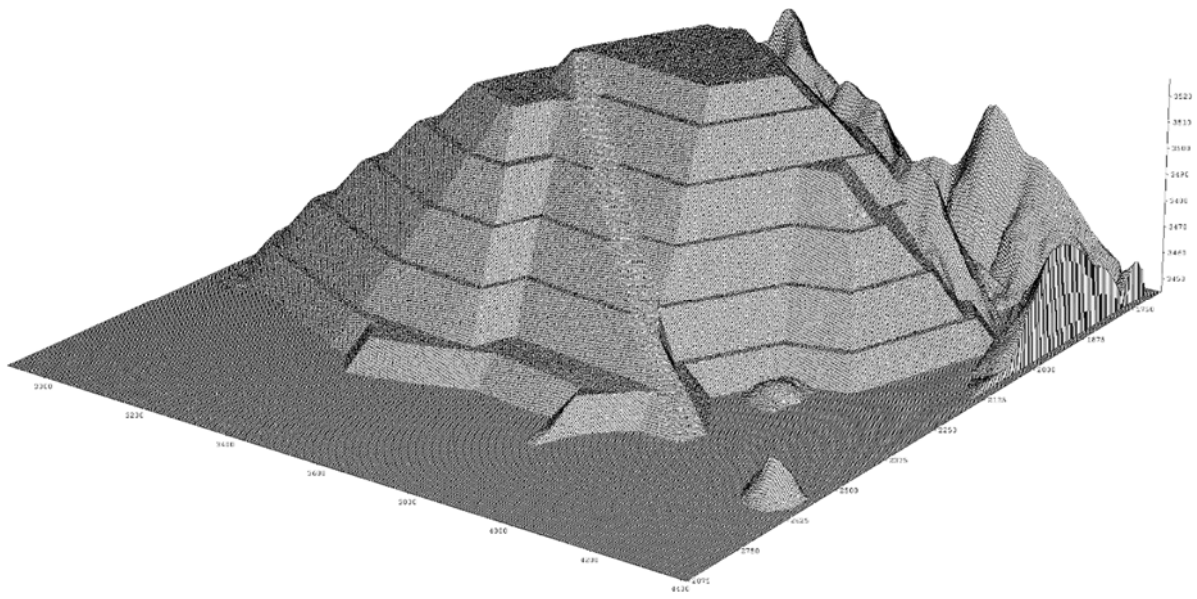


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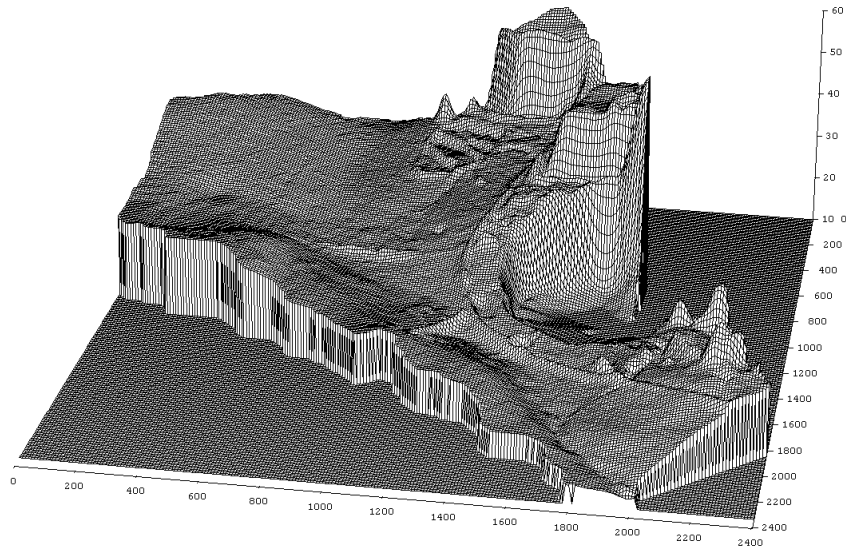
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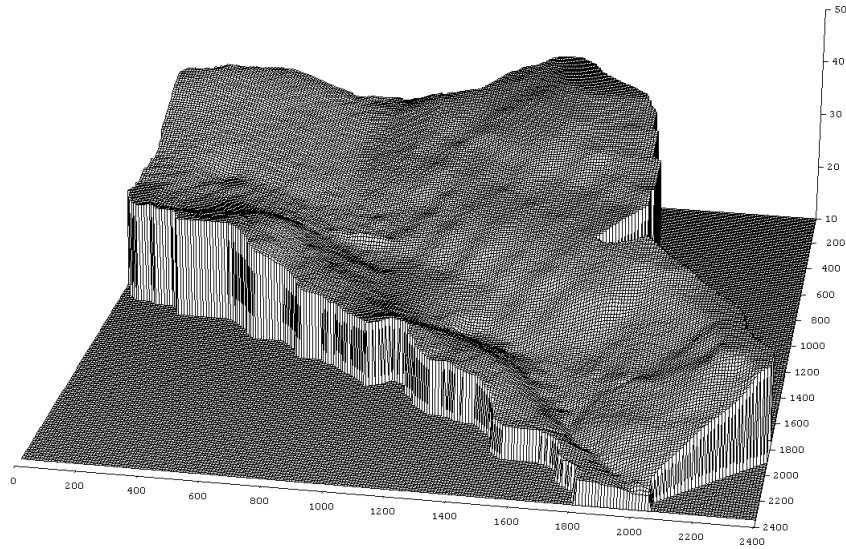
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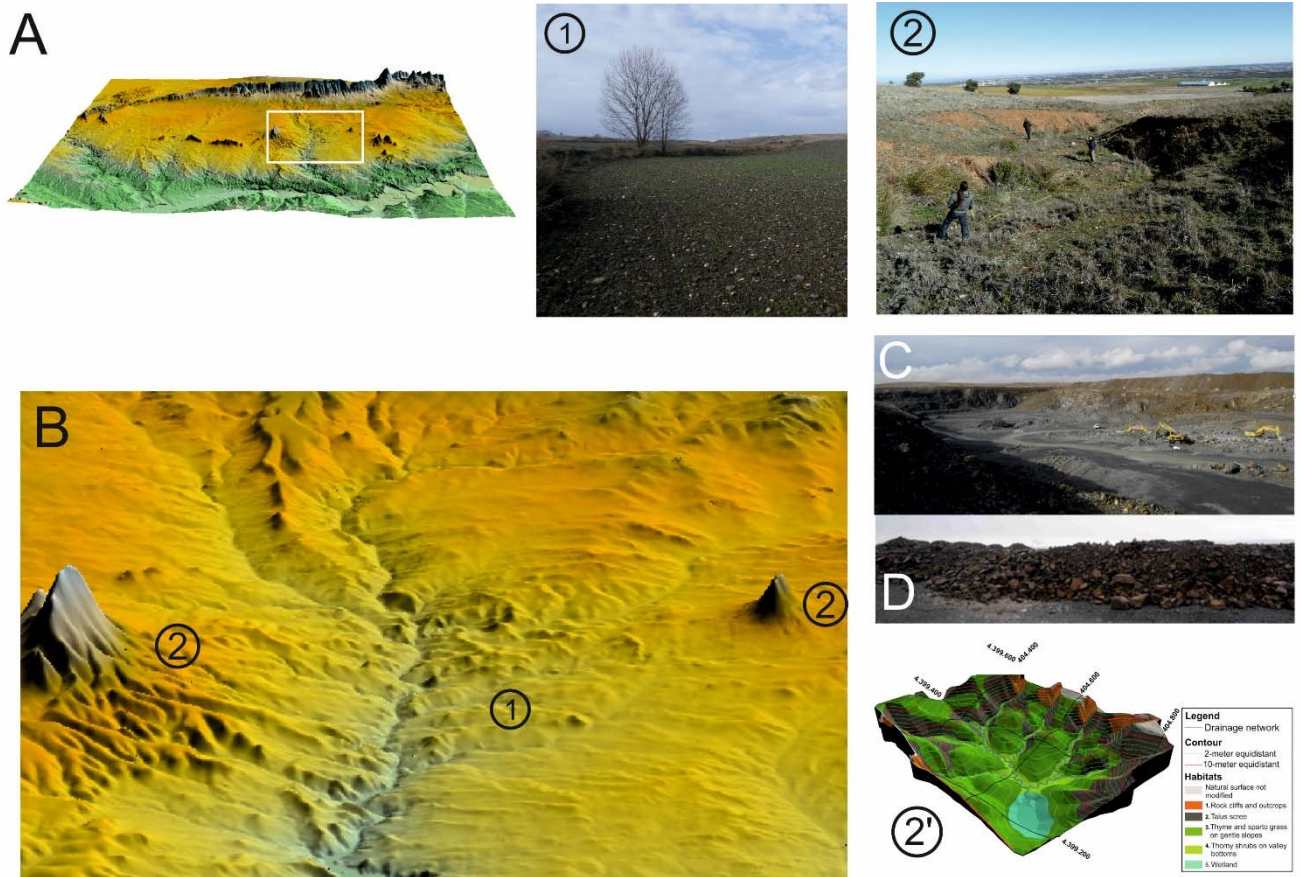
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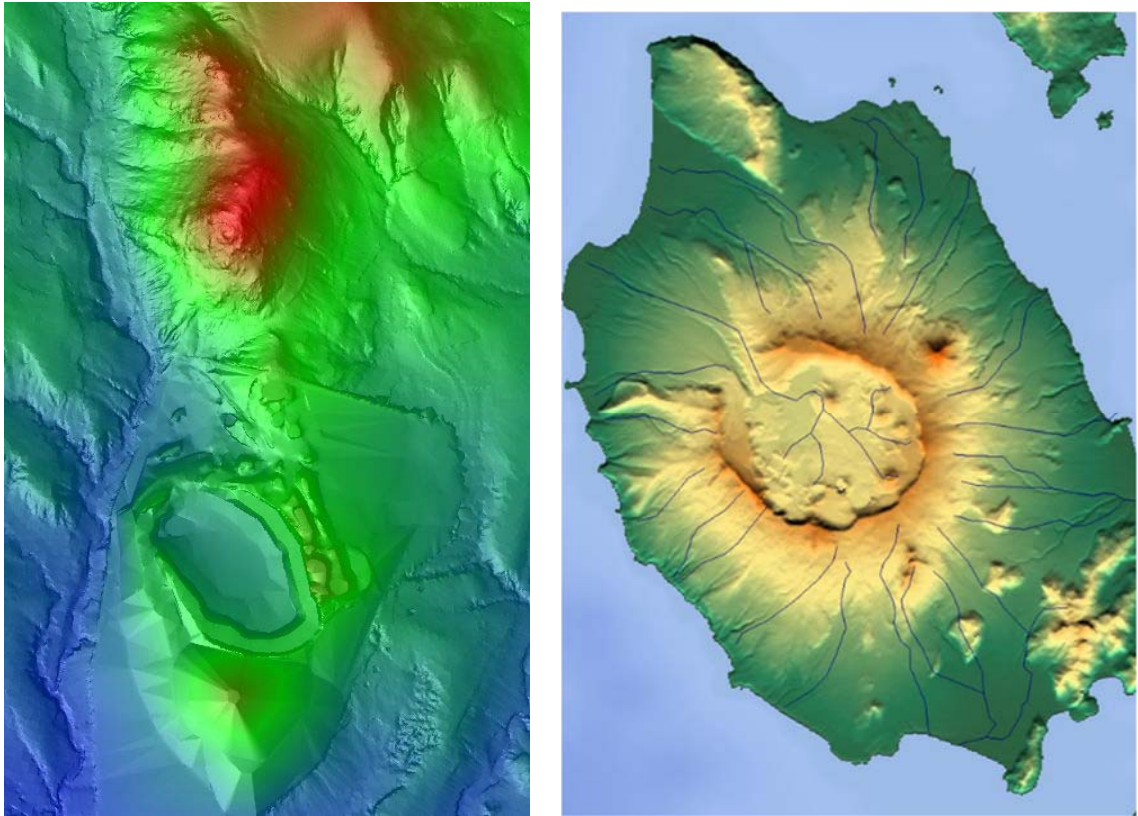


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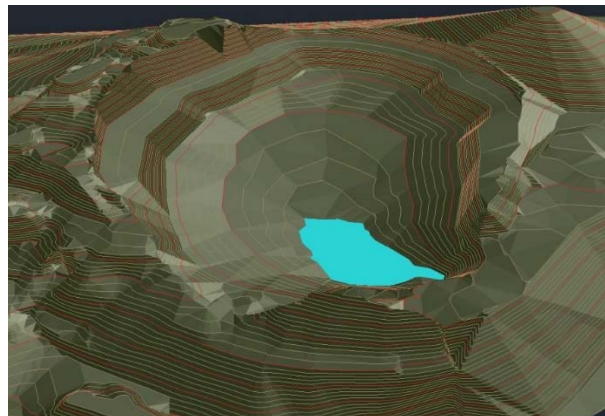
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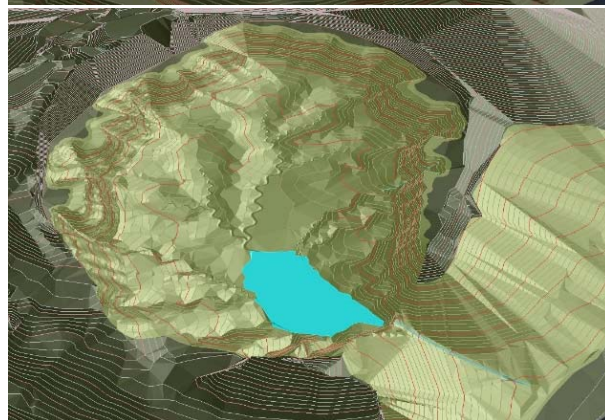
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Table 1. Synthesis of Geomorphic landform design methods and Soil erosion and Landscape Evolution Models, and related software, for mine rehabilitation.

APPROACH	METHOD	RELATED SOFTWARE	FIRST AND KEY REFERENCES / WEBSITE	YEAR	MAIN COUNTRIES
<b>I. GEOMORPHIC LANDFORM DESIGN METHODS</b>					
<b>1. Fluvial Geomorphic approaches</b> <i>for designing drainage systems and related hillslopes, at watershed scale, in non-consolidated materials</i>	1.1. Rosgen	RiverMorph	Rosgen (1994, 1996) <a href="http://www.rivermorph.com/">http://www.rivermorph.com/</a>	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) <a href="http://www.carlsonsw.com/solutions/mining-solutions/natural-regrade/">http://www.carlsonsw.com/solutions/mining-solutions/natural-regrade/</a>	1999	United States, Spain, Australia, Colombia
	1.4. QUEL		Ibbitt et al. (1999); Willgoose et al. (2001)	1999	Australia
<b>2. Hard-rock Natural Landform Replication</b> <i>for designing landforms characteristics of hard-rock natural cliffs, valleysides, steep slopes</i>	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 <sup>R</sup>		<a href="http://www.2g.fr/">http://www.2g.fr/</a>	1995	France
<b>II. SOIL EROSION AND LANDSCAPE EVOLUTION MODELS</b>					
<b>3. Soil Erosion Models</b> <i>Provide erosion rates at the hillslope scale, do not actively adjust the hillslope through time</i>	3.1. RUSLE	RUSLE 1.06, RUSLE 2.0 (for mining, construction and reclamation lands)	<a href="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/">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/</a> Toy et al. (1999)	1999	United States Australia
	3.2. MUSLE - IECA		Fifield (2004)	1994	United States
	3.3. WEPP	WEPP	<a href="https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/wepp/research/">https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/wepp/research/</a> Lafren et al. (1991)	1991	United States Australia
	3.4. SEDCAD	SEDCAD	<a href="http://www.mysedcad.com/">http://www.mysedcad.com/</a>	1987	United States
<b>4. Landscape Evolution Models</b> <i>Provide erosion rates, type of erosion and actively adjust the hillslope and provide 3D visualization of evolving landform</i>	4.1. SIBERIA	SIBERIA, MOSCOW	<a href="http://www.telluricresearch.com/siberia-homepage.html">http://www.telluricresearch.com/siberia-homepage.html</a> (Willgoose, 2018)	2018	Australia
	4.2. CAESAR-Lisflood	CAESAR-Lisflood	<a href="https://sourceforge.net/projects/caesar-lisflood/">https://sourceforge.net/projects/caesar-lisflood/</a> (Coulthard et al., 2013)	2013	United Kingdom, Australia

