Vol. 146, No. 4 · Review article

DIE ERDE

Journal of the Geographical Society of Berlin

Small-scale opencast mining: an important research field for anthropogenic geomorphology

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Manuscript submitted: 1 June 2015 / Accepted for publication: 9 November 2015 / Published online: 17 December 2015

Abstract

Artisanal and small-scale mining (A&SM) is a growing economic sector in many third-world countries. This review focuses on anthropo-geomorphic factors and processes associated with small-scale opencast mining (SSOM), a form of A&SM in which near-surface ores are extracted by removing relatively thin covers of soil, bedrock or sediments. Being widespread and commonly conducted without proper planning and beyond the control of local authorities, this form of mining has potentially large impacts on landforms and landscape dynamics, often resulting in drastic consequences for the local environment and agriculture. SSOM should be regarded as a component of anthropogenic geomorphology because it involves the role of humans in creating landforms and modifying the operation of natural geomorphological processes, such as weathering, erosion, transport and deposition. By initiating new and modifying natural geomorphic processes, SSOM causes and/or accelerates geomorphic processes, resulting in various forms of land degradation. While the direct geomorphic impact of SSOM is in general easily discernible and leads to characteristic features, such as excavated pits and overburden spoil heaps, many secondary impacts are attributed to geomorphic processes triggered in the wake of the primary mining-induced landscape alterations. The magnitude of such secondary implications may well extend beyond the actual mining areas, but these effects have not been thoroughly addressed in the research so far. This review summarizes the known studies on the geomorphic impacts of SSOM operations and highlights common geomorphic processes and landforms associated with this type of anthropogenic activity, thus establishing a starting point for further in-depth research.

Zusammenfassung

Kleinbergbau ist ein wachsender ökonomischer Sektor in vielen Dritte-Welt-Ländern. Dieser Übersichtsbeitrag konzentriert sich auf anthropo-geomorphologische Faktoren und Prozesse, die in Verbindung stehen mit kleinskaligem Tagebau, einer Form des Kleinbergbaus, bei der oberflächennahe Erze gewonnen werden, indem relativ geringmächtige Boden-, Gesteins- oder Sedimentbedeckungen abgetragen werden. Weit verbreitet und gewöhnlich ohne angepasste Planung und Kontrolle lokaler Behörden durchgeführt, hat diese Form des Bergbaus potenziell große Auswirkungen auf Oberflächenformen und die Landschaftsdynamik, was oft drastische Konsequenzen für die lokale Umwelt und Landwirtschaft hat. Kleinskaliger Bergbau sollte als Element der anthropogenen Geomorphologie betrachtet werden, da er die Rolle des Menschen bei der Schaffung von Oberflächenformen und bei der Modifikation von natürlichen gemorphologischen Prozessen beinhaltet, z.B. Verwitterung, Erosion,

Byizigiro, R. Vaillant, Thomas Raab and *Thomas Maurer* 2015: Small-scale opencast mining: an important research field for anthropogenic geomorphology. – DIE ERDE **146** (4): 213-231

DOI: 10.12854/erde-146-21

Abtragung und Sedimentation. Kleinskaliger Tagebau verursacht und/oder beschleunigt die Geomorphodynamik aufgrund der Initiierung neuer und der Veränderung natürlicher geomorphologischer Prozesse, so dass unterschiedliche Formen der Devastierung resultieren. Während die direkten geomorphologischen Folgen des kleinskaligen Bergbaus im Allgemeinen leicht erkennbar sind und zu charakteristischen Merkmalen führen (z.B. Gruben oder Halden), sind die sekundären Folgen einer Geomorphodynamik zurechenbar, die im Zuge der ersten bergbauinduzierten Landschaftsveränderungen ausgelöst wurde. Das Ausmaß dieser sekundären Implikationen kann die aktuellen Grenzen des Bergbaureviers weit überschreiten, aber diese Effekte waren bisher kaum Gegenstand der Forschung. Dieser Beitrag fasst die bekannten Studien zu geomorphologischen Folgen des kleinskaligen Tagebaus zusammen und beleuchtet die wesentlichen geomorphodynamischen Prozesse und Oberflächenformen, die mit diesem Typus der anthropogenetischen Geomorphologie verbunden sind. Damit wird der Ausgangspunkt für weitere eingehende Forschung gelegt.

Keywords Small-scale opencast mining, anthropogenic geomorphology, factors, processes, landforms

1. Introduction

Artisanal and small-scale mining (A&SM) has become one of the developing world's most important activities, contributing significantly to local employment, foreign exchange earnings and national gross domestic product (GDP) (*Hilson* 2002b). A&SM refers to mining by individuals, groups, families or small cooperatives with minimal or no mechanization, often in the informal (illegal) sector of the market (*Dreschler* 2001), using only rudimentary mining and processing methods (*Sousa* et al. 2010). A&SM is therefore very labour-intensive and is conducted by manual operations based on picks, shovels and basins or by employing machinery in a small capacity (*Dorner* et al. 2012, *Lahiri-Dutt* 2003). Such mining activities are usually confined to deposits that are shallow in depth and small in extent (*Lahiri-Dutt* 2003). Small-scale opencast mining (SSOM) is a form of A&SM characterized by open cut techniques to extract easily accessible, near-surface ores covered by relatively thin layers of overburden soils or bedrock (*Kinabo* 2003), which is stripped from the surface to expose the ore. As opposed to industrial large-scale opencast mining, SSOM uses less sophisticated machinery or none at all and employs mostly semi-skilled workers. On the other hand, SSOM has significantly lower requirements in terms of implementation time and initial investment (*Hilson* 2002b). Approximately 30 million people worldwide are employed directly and indirectly in small-scale mining operations (*Sousa* et al. 2010; *Buxton* 2013) and a further 100 million people depend on it for their livelihood, compared to only ~ 7 million people worldwide employed in large-scale industrial mining (*Dorner* et al. 2012). SSOM is thus recognized as the most widespread mining operation practiced in developing countries, where the population is increasing at a higher rate relative to the rest of the world (*Waugh* 2009). These numbers are growing in line with higher demand for minerals both in developing countries and emerging economies, such as China and India (CASM 2013, *Heemskerk* 2005a). *Hilson* and *Garforth* (2012) argue that agricultural poverty, or the hardship induced by an over-dependency on farming for survival, has fuelled the recent rapid expansion of A&SM operations in areas such as the Sub-Saharan region. Environmental problems caused by A&SM are thus specific for developing countries and are seriously aggravated by the fact that operations lack proper planning or official control, commonly pay little attention to the disposal of waste products, and almost never apply adequate reclamation measures (*Mallo* 2012).

Recent studies have highlighted the capability of SSOM activities for landscape change and geomorphic processes with low-intensity research. Among the most significant geomorphologic impacts are landform alteration and accelerated soil erosion (*Dentoni* and *Massacci* 2012). The sector is part of anthropogenic geomorphology which, according to *Szabó* (2010), focuses on the wide and ever-widening range of surface landforms, extremely diverse in origin and in purpose, created by the operation of human society. For instance, *Hilson* and *Garforth* (2012) link physical changes in the environment initiated by small-scale mining to (i) the labour-intensive mineral extraction and processing techniques applied in developing countries, (ii) the inadequate confinement of tailings, and (iii) their uncontrolled discharge across the landscape, resulting in a number of environmental problems. The removal of overburden material and the formation of tailing heaps alter hillslope stability (*Kainthola* et al. 2011). Consequently, the allocation of easily erodible material from tailings or landslides often results in increased turbidity and sediment yield in streams (*Sousa* et al. 2010). Because the major impacts of mining on land can occur before, during and after mining operations, the influence on the environment can extend far beyond the mined area (*Lottermoser* 2003). As a great number of these activities are difficult to impede, small-scale mining activities may increase further, thus becoming even more environmentally destructive in the future (*Hilson* 2002a). Furthermore, land degradation is controlled not only by the specific mining techniques applied but also by different natural factors that govern geomorphic processes in the landscape, such as topography, slope stability, soil erodibility and vegetation cover whose properties are actually disturbed.

Understanding these factors and processes is crucial for the assessment of mining-induced land degradation and the implementation of proper techniques as well as for the development of adequate mitigation measures (*Toy* et al. 2002). The lack of knowledge on how to address the specific environmental problems arising from A&SM creates, according to *Zhang* et al. (2011), a ''grow first, clean up later'' mentality, particularly in developing countries. Several projects to enhance environmental awareness in developing and threshold countries were launched in recent years. For example, the China Australia Research Institute for Mine Waste Management, 'CARIM, 1994-1997', developed a set of guidelines to give the industry direction for establishing best-practice environmental management (*Freak* 1998). In Central Africa, an international German project, 'Coltan Environmental Management (CEM)', was launched in 2007. The project was conceived to develop science-based but tangible 'how-to-do' pre-cautionary and mitigation strategies (*Biryabarema* et al. 2008). Operating independently on different continents, both projects address the same problem: As arable land in densely populated regions of Africa (*Biryabarema* et al. 2008) and Asia (*Freak* 1998) becomes increasingly scarce, proactive steps are needed to mitigate mining-related land degradation and foster mine site rehabilitation research, with a focus on sustainable post-mining agricultural land use (*Freak* 1998, *Biryabarema* et al. 2008). Along the same lines, *Lóczy* (2010) emphasizes that human activities with geomorphic effects are an integrated part of environmental management, encompassing both the utilization of environmental resources and the simultaneous protection of environmental values. Many studies and international scientific debates have discussed the best approaches for sustainable management of natural resources, particularly to avoid the causes of on-going land degradation and loss of fertile soils. They all assert that the resources and by-products of water, soil and waste are all interconnected and have dependent relationships with one another, thus forming a nexus (*Lawford* 2015). Soil being one of the non-renewable natural resources that is often severely impacted by SSOM, all debates call for the urgent broad adoption of sustainable land management practices in areas affected by anthropogenic activities (http://globalsoilweek.org). Furthermore, *Szabó* (2010) stresses that geomorphologists must study the problem of artificially created landforms because they have many influences on the environment and because the anthropo-geomorphic impact is growing exponentially. Therefore, a better understanding of the interrelated dynamics of the water-soil-waste nexus would allow for improved production efficiency with a long-term benefit for sustainable development (*Lawford* 2015).

However, the many studies investigating the environmental impact of SSOM have mainly focused on either stream contamination or social, economic and legal issues (e.g., *Mallo* 2012). The existing studies that assess geomorphologic aspects are limited to quantifying mining-induced soil losses, but little is known about other factors controlling geomorphologic processes in landscapes affected by SSOM. This review, supported by a few landforms photos taken during our field survey, aims to enhance the understanding of the impacts of SSOM as a new and important research field for anthropogenic geomorphology by summarizing the existing literature and drawing conclusions based on a synopsis of the available relevant studies.

2. Global significance of SSOM as a potential geomorphic agent

As mentioned in the previous section, SSOM is one of the human activities responsible of sculpturing the earth surface. *Hooke* (1999) stresses that no other geomorphic agent appears to be as effective, currently, in reshaping the surface of the Earth. His statement was based on figures showing the contribution of major erosive agents in sediment yield delivery: The human species annually displaces approximately 35 Gt, yet rivers presently deliver only 24 Gt of sediment to the oceans and interior basins, of which 10 Gt is estimated to be a direct result of agriculture.

Table 1 Examples for wastes and derelict lands resulting from SSOM in selected developing regions

Country	Waste production/derelict	Reference
Malaysia	200,000 ha tin mining land derelict	*Hossner* and *Hons* 1992
Brazilian Amazon	SSOM moves more than 4 million m^3 of material annually	*Hinton* et al. 2003
Suriname	Water transparency: between 0-50 cm in small creeks and from 50-70 cm in larger rivers	*Heemskerk* and *Van der Kooye* 2003
Nigeria	321 km^2 affected by opencast mine wastes	*Hossner* and *Hons* 1992
Himalayan region of India	More than 60 % of land covered by mine wastes	*Ghose* 2003b
Zimbabwe	4,600 km of riverbeds are worked by 200,000 small-scale miners	*Lombe* 2003

Although sediment delivered by SSOM is not well documented, this anthropogenic activity may contribute significantly to Earth surface dynamics because it is the most widespread form of mining in less advanced countries. In developing countries, approximately 90 % of mines are small-scale operations (*Ghose* 2003a; *Lombe* 2003). In spite of their rudimentary and migratory nature, these operations involve large areas and feature poor environmental management practices and safety conditions (*Ghose* 2003b). Thus, geomorphic processes operate on mining wastes and mine wastelands as well.

According to *Li* (2006), mining wastes include waste rocks, overburden, slag and tailings on the land surface, whereas mine wastelands generally comprise the barren stripped area, loose soil piles, waste rock and overburden surfaces, areas of subsided land, tailing dams and other land degraded by mining facilities. A few figures of physical impacts associated with SSOM are provided in *Table 1*.

Throughout the literature, there is a fairly broad consensus about the range of geomorphic impact caused by SSOM. Soil erosion heads the list. Renowned for its pervasiveness, soil erosion is often poorly monitored and threatens organisms, stream dynamics and habitats. Surface erosion has both on-site effects related to the loss of topsoil and off-site effects associated with downstream siltation (*Mol* and *Ouboter* 2004; *Adler Miserendino* et al. 2013). It can also result in hydrological modification (impact on rivers and streams due to physical disruption of banks and vegetation) and general destruction of vegetation (*Sindling* 2003).

SSOM sites may pose extremely stressful conditions for restoration because (i) restoration planning is extremely lacking and (ii) most SSOM sites are scattered and located in remote areas, outside of the effective control of government agencies (*Li* 2006). In his review of issues related to SSM, *Noetstaller* (1987) summarized suggestions of classification of mining mainly based on the annual quantitative production, differentiating between the overburden outputs of underground and surface mining (*Table 2*).

Table 2 Size classification of small-scale mines based on annual mining output (source: Noetstaller 1987)

Size segment	Underground mining	Surface mining
VSSM	5,000	below 10,000
SSM	5,000-50,000	10,000-100,000
MSM	50,000-500,000	100,000-1,000,000
LSM	above 500,000	above 1,000,000

VSSM: very small-scale mine; SSM: small-scale mine; MSM: medium-scale mine; LSM: large-scale mine

Table 3 Classification of mining scales for selected minerals in China (unit: tons), source: Ziran 2003

Mineral	Unit (ores)	Large-scale	Medium-scale	Small-scale
Coal	× 100,000	> 9	3-9	< 3
Iron ores	× 100,000	> 20	6-20	< 6
Copper, lead, zinc bauxite, tungsten, tin	× 100,000	> 10	3-10	< 3
Gold	× 100,000	> 15	6-15	< 6
Phosphate	× 100,000	> 10	5-10	< 5
Pyrite	× 100,000	> 5	2-5	< 2

In China, small-scale mines are classified into three categories (*Ziran* 2003): “large”, “medium” and “small” (*Table 3*). The classification is based on the tonnage of ores and minerals or oil and gas extracted, depending on ore type, but the ranges are slightly different from those of other authors (*Ziran* 2003; *Shen* and *Gunson* 2006).

A coal mine with a production capacity of less than 300,000 tonnes of ore per annum would be considered a small mine, whereas a gold mine with a production of 600,000 tonnes of ore per annum would be considered a small mine. Coal mines ranging between 300,000 and 900,000 tonnes per year would be “medium-scale”, and those with a production exceeding 900,000 tonnes per year would be “large-scale”.

Within the A&SM category, SSOM has the most severe impact on the environment, which is mostly attributable to the techniques and methods used. *Li* (2006) stressed that, during opencast mining, 2-11 times more land is damaged than with underground mining. The Environmental Protection Agency (1976) reported that sediment production from surface mined areas can be 100 to 2,000 times that from a forested area and more than 10 times that from grazing lands.

Within each factor, either anthropogenic or natural, there are a number of associated processes, which is why the two components are treated together.

3. Techniques and methods of SSOM and their direct environmental impact

The extraction and mass translocation techniques commonly employed in SSOM are the most basic factors regarding anthropo-geomorphic impact. A synopsis of the common grades of technology and organization involved in SSOM operations is provided in *Figure 1*. In spite of the different levels of mining operation, small-scale mining techniques generally have the following characteristics:

(i) either open cut or shallow underground mining, using simple equipment and methods and minimal investment of infrastructure and processing plants (*Sindling* 2003);

(ii) heavy reliance on manual labour (UN 1972; *Dreschler* 2001; *Bugnosen* 2003);

(iii) if partners from developed countries are involved, these operations may have industrial characteristics with relatively advanced degrees of mechanization, internal organization and compliance with international industrial standards, while still operating at a small scale (*Hentschel* et al. 2003).

The extent of the impact of mining is believed to depend on the type and scale of the mining operation (*Stottmeister* et al. 2002). Attempts were undertaken to place SSOM into categories: ‘artisanal’, ‘traditional small-scale’ and ‘advanced small-scale’ (*Kambani* 1995; *Masialeti* and *Kinabo* 2003; *Hentschel* et al. 2003) based on ‘grades of technology’ and organization characterizing the sector (*Fig. 1*).

3.1 Grades of technology within SSOM

(i) **Artisanal mining** refers to the smallest and simplest of operations. These operations feature simple tools and are informal business enterprises. They can take the form of spontaneous practice without title to property as well as activities with a registered claim to the land plot. Artisanal mining is predominantly perpetuated

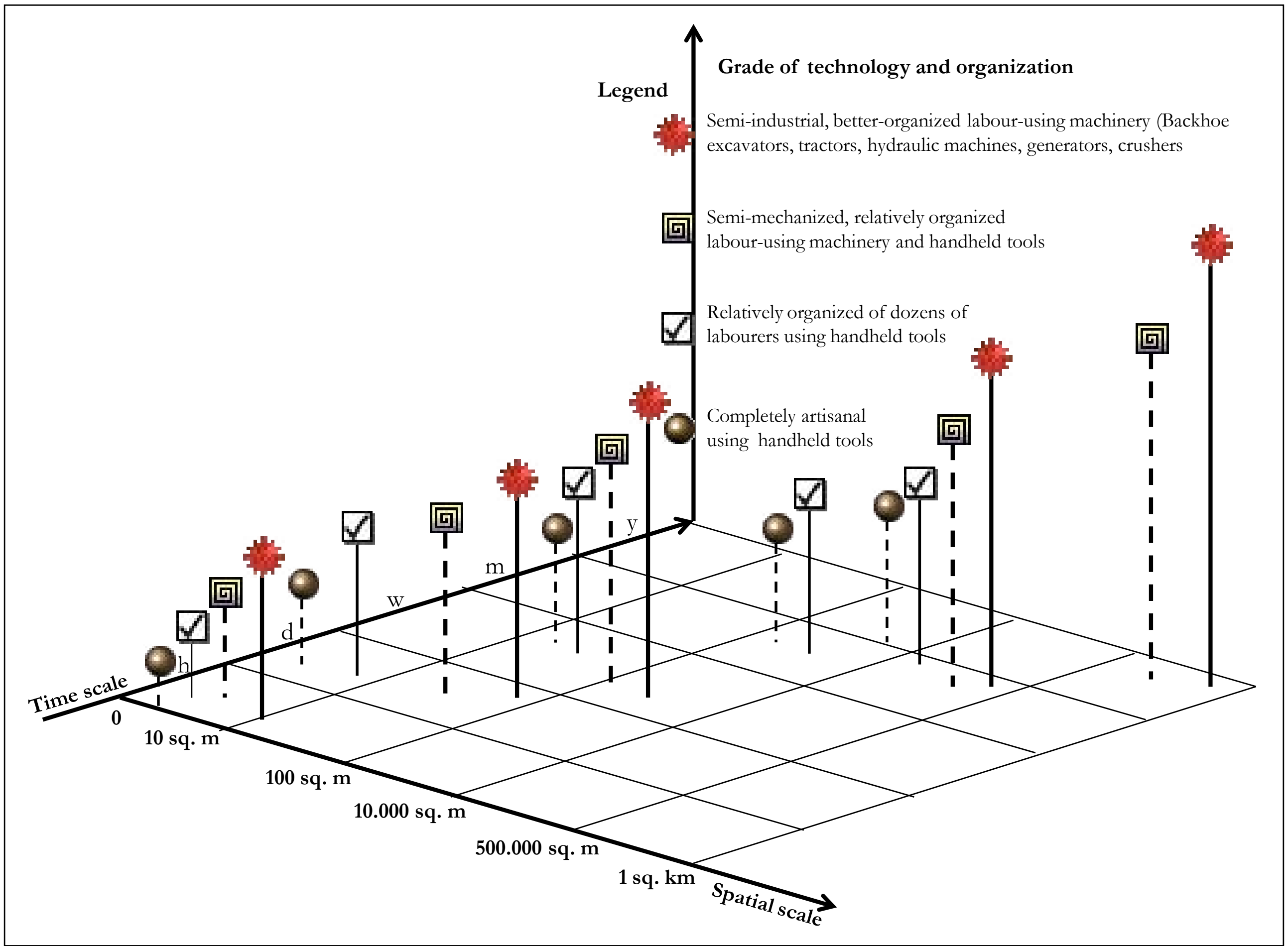

Fig. 1 Grade of technology – organization and potential intensities regarding geomorphic processes (Byizigiro, 2015). The three-dimensional figure represents the types of techniques used in SSOM by relating them to a relative time frame of mining operation and the extent of land that is involved or disturbed. This may serve as a baseline from which further investigation of the impacts of individual techniques can be undertaken. The intensity of landscape development within SSOM sites will depend on the grade of technology used and the mechanisms implemented to mitigate the resulting impacts.

by illegal miners known as "phantom soldiers " who move swiftly to a reported new find.

(ii) **Traditional small-scale mining** is comprised of the registered and licensed non-mechanized or semi-mechanized operations run by society members or entrepreneurs with the use of hired labour. These operations have a basic management structure and lack financial resources as well as appropriate management and technical skills. There are two sub-branches within this category, (ii. a) non-mechanized and (ii. b) semi-mechanized, because the grades of technology used by these two types of operations are not the same.

(iii) The terms a**dvanced small-scale** (*Kambani* 1995) or **semi-industrial mining** (*Hentschel* et al. 2003) are used interchangeably and refer to a category of legally constructed SSM with advanced mechanization and management, which undertakes reasonable geological investigation and mine planning (*Kambani* 1995).

Because of their advanced nature, they more or less comply with mining requirements because they work as subcontractors for the large-scale mining industry from industrialized countries (*Hentschel* et al. 2003). However, the sector is small-scale because the labour force is not formally trained for mining (*Heemskerk* 2005a).

Techniques associated with SSOM, both hillside and alluvial mining, are generally limited to superficial or near-surface ore-bearing rock formations (*Aryee* 2003). Furthermore, most small-scale mining licenses are not based on initial exploration work. The confirmation of ore deposits is based frequently only on a few randomly collected surface samples that are not representative and excavation is started with little or no pre-operational exploration and planning (*Aryee* 2003). This results in scattered excavations, aggravating local landscape disturbance (*Noetstaller* 1987; *Aryee* 2003).

After potential ore deposits are located, several methods are applied for exploitation. For both hillside and alluvial mining, pits or holes and trenches are dug, and the overburden is removed using shovels. When the mineral-bearing horizon is reached, the ore is then extracted using picks and shovels and heaped on the ground. Small-scale mining operations have not changed significantly over years. They are mostly manual and very labour-intensive, using simple means such as picks, shovels, chisels and basins or using some degree of mechanization, e.g., heavy machinery, on a small scale (*Aryee* 2003; *Hilson* 2002b, *Fig. 2*)

3.2 Extraction methods

The extraction methods described here are related to anthropo-geomorphic processes that are described further, along with anthropogenic factors, in the following sections. These methods are generally placed into three categories:

(i) **Shallow alluvial mining** refers to placer mining or 'dig and wash' techniques, which are used to mine alluvial deposits typically in valleys or low-lying areas with little or no overburden. These deposits are typically at depths of less than three metres (*Aryee* 2003) (*Fig. 2A*).

(ii) **Deep alluvial mining** involves the extraction of deep alluvial deposits from the banks of

Fig. 2 Techniques and methods associated with SSOM. A. Shallow alluvial mining. B. Deep alluvial mining (Chirico and Malpeli 2013). C. Lode mining. D. Simple sluice box. E. Ground sluicing. F. Panning using plastic tray with riffles (Veiga et al. 2006). G. Mechanized SSOM using bulldozer in Gatumba, Rwanda. H. Mineral concentration using electrical shaking tables, Gatumba, Rwanda. I. Hydraulic mining (Heemskerk 2005b). Apart from B, D, F and I, all other photos were taken in Ruhanga and Nkokwe mines, Gatumba Mining District, Rwanda (Byizigiro, 2008-2014).

major rivers. Techniques involve excavating a pit and digging until the mineral-bearing gravel horizon, typically located at a depth of seven to 12 metres is reached (*Aryee* 2003) (*Fig. 2B*). During the mining operations, the sides of pits are shaped into terraces or benches to ensure that they do not collapse.

(iii) **Hard rock** or **lode mining** refers to the mining of mineralized veins, also called primary deposits. This type of mining is used to mine both shallow and deep mineral-bearing rocks. Holes are sunk to intercept the rocks, which are then worked along strike (*Aryee* 2003). Where the rocks are weathered, small-scale miners use chisels and hammers to break the ore. If hard bedrock is encountered, explosives are commonly used to obtain the ore (*Fig. 2C*).

However, the level of technology does not allow mining of ore at great depths. Access via shafts generally involves old metal structures and footholes made in the shaft walls (*Eshun* 2005). The loosening of rocks is often by means of hand-held hammers, chisels, mattocks and shovels. The miners carry torches and hurricane lamps to illuminate their work areas (*Eshun* 2005).

3.3 Processing methods

The processing methods used in SSOM to extract the minerals rely on relatively simple hydraulic surface mining methods. These techniques, which have been in use since the 19th century (*Nelson* and *Church* 2012), are mostly based on sluicing, a trapping mechanism which captures particles of heavy minerals through the use of sluices.

Three basic applications are known:

(i) With **simple sluicing**, ore-bearing sediment is shoveled into sluice boxes (*Fig. 2D*) (*Veiga* et al. 2006), then washed out to extract the ore. Sluices are angled such that heavy mineral particles settle out behind riffles or in carpet fibres (*Veiga* et al. 2006). Because the material must be fluidized for this process to work, artisanal miners commonly use substantial amounts of water and modify the hydrologic systems (e.g., river diversions, tailings beaches). Various sizes of sluices are used, from small hand-fed sluices to large sluices on dredges or fed by trucks, front-end loaders or bulldozers, which can process as much as 150 m^3 of alluvial ore per hour (*Veiga* et al. 2006).

(ii) In **ground sluicing** (*Fig. 2E*), a stream is diverted to erode material that is then flushed into a sluice channel (*Cuadra* and *Dunkerley* 1991). This operation is started by cutting a trench across the area to be worked in order to provide a water course that, when reaching bedrock, becomes the ground sluice. A ditch is brought to the top of the bank to be mined, allowing a stream of water to cascade over the working face and flow through channels at the base of the gravel bank (*Griffith* 1960).

(iii) In **hydraulic mining** (*Fig. 2I*), high-pressure water is sprayed against the walls of a mine to excavate sediments. Water is redirected through an ever-narrowing channel into a large canvas hose, and sprayed out of a large iron nozzle, known as a “monitor”. The high-pressure stream can overturn hundreds of cubic metres of materials within a very short time (*Hunerlach* et al. 1999).

The most commonly used mineral concentration techniques related to SSOM are gravity concentration and comminution (*Veiga* et al. 2006).

Gravity concentration is a process used to concentrate the mineral of interest that relies on the difference in specific gravity between the mineral and the gangue minerals. It involves **sluicing** and **panning** (*Fig. 2F*) (*Veiga* et al. 2006). Panning is the most ancient form of gravity concentration. Circular or back-and-forth shaking of ore and water in a pan causes the ore to stratify as the heavy minerals settle to the bottom of the pan, allowing the lighter gangue to be washed off the top. Panning is the basic means of recovering minerals from alluvial and high-grade primary ore in SSOM.

Comminution is the technical term used to describe the mechanical disintegration of a rock, which is done by **crushing** (coarse) and **grinding** (fine), or by simply breaking up clumps of soil or clayey materials, subsequently eliminating or discarding the undesirable material, also called “gangue minerals” (*Veiga* et al. 2006). Crushing typically occurs through the pinching of a rock between two metal plates (jaw, gyratory or cone crushers) or through the impact of a metal surface on a rock (hammer or stamp mills), whereas grinding is performed on already crushed material to achieve an adequate particle size for the efficient extraction of the ore. As tailings in the form of easily erodible material are commonly discharged into the environment due to a lack of storage facilities (*Tarras-Wahlberg* 2002), these operations may have a significant impact on local geomorphic processes.

4. Factors controlling geomorphological development at SSOM sites

Geomorphic processes at SSOM sites are controlled by direct anthropogenic intervention and natural factors. The presence of both operating on the same site increases the rates of soil loss relative to the action of natural erosion agents alone. Both anthropogenic and natural factors are associated with a number of processes, which are described below.

4.1 Direct anthropogenic disturbance

Goudie (2006) differentiated two types of processes associated with anthropogenic intervention, namely direct and indirect processes. Direct interventions or impacts are usually conscious, leading to clearly recognizable consequences, e.g., mine pits and slopes (*Goudie* 2006). The less readily identifiable outcomes of anthropogenic interventions, however, are attributable to natural processes that are modified or intensified, e.g., translocation of sediment and high sediment yields to rivers; these factors are the indirect consequences of anthropogenic intervention (*Goudie* 2006, *Rózsa* 2010, *Mbendi* 2015).

In connection with the statement above, a range of processes within directly mined areas and in their surrounding are encountered in SSOM sites. Therefore, the transport of soil and geological materials downslope from mining wastes may occur at different intensities depending on the period of intensive mining and/or the quantity of rainfall. Consequently, these processes may result in rapid changes in the surface appearance and degradation of the soil properties of mine-affected sites (*Stottmeister* et al. 2002).

Zones of influence (*Fig. 3*) can be hypothesized through simple deduction by calculating the area of the mine (A_m) and the area influenced by the mine (A_i) for both large-scale opencast mining (LSOM) and small-scale opencast mining (SSOM).

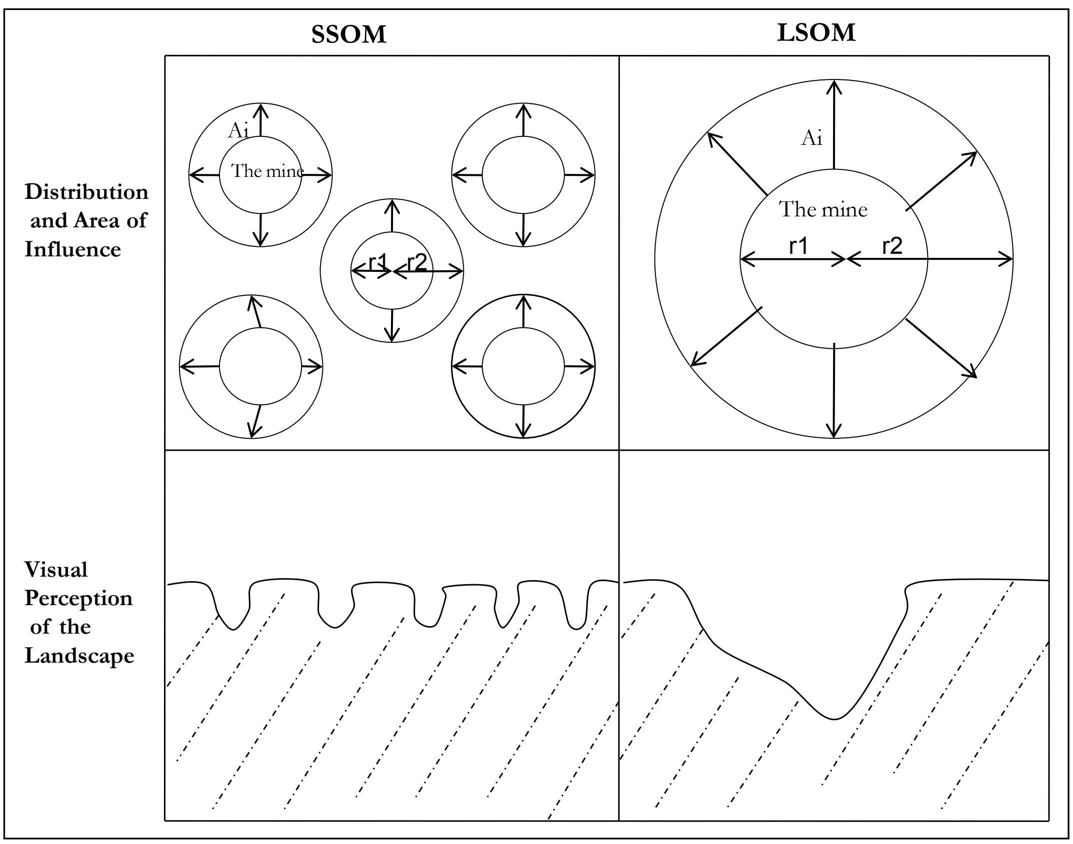

Fig. 3 Hypothetical area of influence of SSOM versus LSOM (Byizigiro, 2015)

$$i = r_2$$
$$r_m(radius\ of\ the\ mine) = r_1 ; r \qquad \text{Equation 1}$$

$$A_m = \pi . r_1^2 \qquad \text{Equation 2}$$

$$A_i SSOM = \sum_1^n \pi r_{2n}^2 - \sum_1^n \pi r_{1n}^2 \qquad \text{Equation 3}$$

$$A_i LSOM = \pi . r_2^2 - \pi . r_1^2 \qquad \text{Equation 4}$$

Unlike in LSOM, where mechanisms for controlling and mitigating negative impacts are implemented during and after mining operations, the scattered nature of SSOM and the lack of proper remedial plans result in influences over larger areas, even though individual local operations are on small areas of land. In India, for example, some 3,000 small-scale mines account for approximately 50 % of the non-fuel mineral production (*Ghose* 2003a). In Ghana, approximately 650 licensed gold SSM groups are in operation (*Mireku-Gyimah* and *Suglo* 1993). While LSM is estimated to provide direct employment to approximately 15,000 Ghanaians, between 100,000 and 200,000 people are estimated to be directly engaged in ASM (*Aubynn* 2009).

Specifically for SSOM, *Table 4* summarizes the processes involved with respect to the main groups of anthropogenic processes suggested by *Goudie* (2006).

Based on excavation, which is one of the major anthropo-geomorphic processes associated with mining and quarrying, *Dávid* (2010) classified the resulting landforms into three main groups: (i) excavated or negative forms, among which the most conspicuous are pits and trenches; (ii) accumulated or positive forms, represented by mine dumps, whose shape is determined by several factors, including the original ground surface, the mode of accumulation and the physical features of the dumped material; and (iii) forms destroyed by quarrying activities, leading to the levelling of the surface, which is known as planation in geography. Particular landforms – both negative and positive landforms – may develop as a result of the excavation and deposition associated with opencast mining (*Walling* 2006; *Table 5*).

Contrary to industrial mining, whose phases of landscape development are known, there are uncertainties regarding the chronosequence of landscape changes at SSOM sites. *Zhang* et al. (2011) state that during the early phases of mineral exploitation in industrial mining, landscape changes in mining areas are rapid and reach their climax in the heyday phase. After deposits are largely exploited, the rate of landscape changes decelerates until changes cease with the closure of mining operations and the application of reclamation measures (*Zhang* et al. 2011).

Table 4 Activities involved in SSOM versus LSOM (modified from Asiedu 2013)

SSOM	LSOM
Mining process	
1. Random sampling, informal prospecting; mining begins with simple handheld tools 2. Cutting vegetation 3. Digging pit 4. Trenching 5. Dredging 6. Panning 7. Sluicing	1. Formal prospecting, stripping of vegetation and soils with bulldozers 2. Terracing 3. Pitting soils 4. Water spraying and pumping 5. Crushing of ore 6. Grinding (finer) in preparation for washing 7. Pilling wastes 8. Conveying mining products
Environment control / remedial mechanisms	
1. No proper mechanism for SSOM site restoration 2. No systematic or sustained rehabilitation plan	1. Preservation / confinement of soil and wastes 2. Refilling the pit by returning waste rock material and soil moved 3. Systematic sustained and implemented rehabilitation plan

Table 5 Anthropo-geomorphological processes and outcomes in SSOM sites (modified from Goudie 2006 and Dávid 2010)

Direct SSOM processes		
Excavation	Construction	Hydrological interference
Cutting and stripping vegetation, digging ditches, pitting, trenching, shallow tunnelling	Tailings dams, mine waste piles, rock dumps, terraces	Diverting stream channel
Indirect SSOM processes		
Siltation of stream and erosion-related sedimentation	Subsidence, collapse, setting	Slope failure/landslide, rill development, flow, accelerated creep
Translocation of mine wastes by natural processes, accelerated hydrological regime dynamics, tailings fan at the outlet of stream, clogging of stream channel	Undercutting of outer bank of stream	Weakening of regolith, crack and fissure development, sliding, increased runoff

The uncertainties associated with SSOM operations, however, relate mainly to (i) the lack of a mining schedule, specifically with respect to mineral exploitation and decommissioning, mostly because the amount and extent of mineral deposits are often not known, and (ii) the lack of proper plans and relevant skills for landscape reconstruction and reclamation of affected sites. Most soil properties may change in areas affected by SSOM. The soils in these areas may reach an equilibrium after 200 to 400 years (*Holmberg* 1983), whereas other properties, such as the distribution of $CaCO_3$, may require as much as 1,000 years to reach the point where they resemble native soils (e.g., *Schaaf* and *Hüttl* 2005).

Moreover, the spontaneous recovery of the landscape relied upon by the sector is compromised because self-recovery suggests that the mine is entirely decommissioned (*Prach* and *Hobbs* 2008).

Opencast mines are therefore still susceptible to trigger mass movements such as slump, rock and landslide among others. Arising landscape changes are bound to last since mine sites are often abandoned and there is often little commitment to apply efficient mitigation measures.

4.2 Natural factors

SSOM may either initiate new geomorphic processes or process cascades or modify (accelerate but also decelerate) geomorphic processes that were already occurring in the natural system. These process dynamics are externally triggered by precipitation but are also controlled by internal structures, such as (top-)soil properties and topography that are actually altered by mining activities. Geomorphic processes may therefore operate at an accelerated rate, which results in rapid re-sculpturing (degradation or aggradation) of landforms.

In SSOM sites, excavation can take many forms. The most common include trenching, pitting and sometimes shallow tunnelling. The processes associated with excavation can result in mass movement, such as sliding, slumping of rocks and/or regolith and sometimes localized subsidence. Trenching increases the shear stress on inclined surfaces. When soil is sheared due to large displacement under constant effective normal stress, the shear stress reaches the peak strength with increasing shear displacement (*Nakamura* et al. 2010). These problematic geo-technical conditions were encountered by *Ghose* (2003b) in the Himalayan highlands, where mining is being conducted at a small scale. Geo-environmental constraints imposed upon mining in this region are related to frequent landslides, debris flows and groundwater seepage. The disposal of mine waste on steep hill slopes poses an additional problem (*Ghose* 2003b). *Yarbrough* (1983) defines subsidence as “the lowering of the strata, including the surface due to underground excavation” that results in sinkhole landforms.

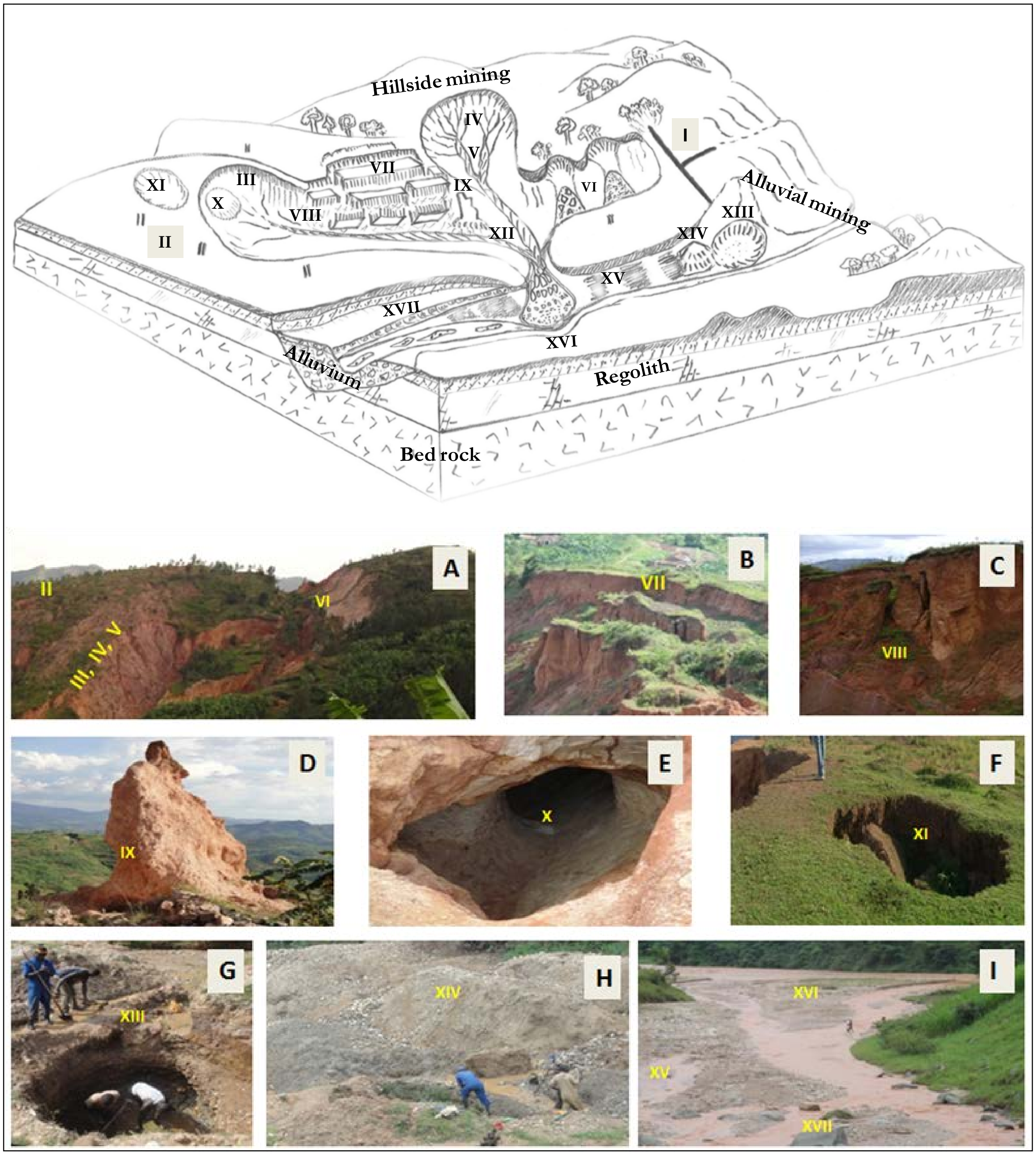

Fig. 4 Overview of hypothetical landforms resulting from SSOM impacts (labels apply to both block diagram and photos): I: Mineralized vein/ore, II: Stumps of cleared vegetation, III: Pit wall, IV: Rills developed on pit wall, V: Gullies, VI: Land slide/rock fall, VII: Slump, VIII: Topples, IX: Stack, X;: Gallery resulting from underground excavation, XI: Sinkhole, XII: Flow track (not represented on photo), XIII: Mine pit, XIV: Tailings dump, XV: Debris flow, XVI: Tailings fan, XVII: Braided stream channel. Photos were taken at Kivuvu mine, Burundi (xi) and Gatumba, Rwanda (Byizigiro, 2008-2014).

Normally, **sinkholes** are landforms typically associated with industrial underground mining. *Harnischmacher* and *Zepp's* study (2014) on the Ruhr mining region describes the **longwall mining** methods as the most suitable for extracting seams with relatively large lateral extents and a fairly consistent thickness. In this method, a panel of coal is removed by working a face of up to 300 m in width between two parallel roadways, more than 1,000 m beneath the surface (*Harnischmacher* and *Zepp* 2014). The roof is supported only near the roadways and at the working face. After the coal has been mined and loaded, the face supports are advanced, leaving the strata in the areas where the coal has been removed to collapse into the caved area. In the Ruhr region, several sinkholes were identified in the landscape, and the highest subsidence value amounted to more than 25 m (*Harnischmacher* and *Zepp* 2014). This type of landform, which was not directly discernable in the field, was identified through comparison of historical and current elevation data. Regardless of the former topography, the authors found that mining subsidence not only captures surface depressions but also elevation features (*Harnischmacher* and *Zepp* 2014).

Although the subsidence process and its resulting sinkhole landform are rare in SSM sites, *Yarbrough* (1983) recognizes that regardless of the depth of mining, it is possible that surface subsidence may occur as a result of the removal of material from underground, thereby inducing instability in the overlying strata. *Marschalko* et al. (2014) describe how this process begins in the overlying geological environment and spreads vertically towards the ground surface and laterally through the bedrock. They explain that caving has a time sequence. It starts with roof weighting, continues with panel fallouts and finishes through a collapse of the underground space.

As described above, the geomorphic processes and their outcomes suggest that the engineering properties of soils and regolith in mine sites and their behaviour in response to anthropogenic disturbance are modified. The properties of soil are therefore not uniform in distribution and may change with time (*Howard* and *Jahns* 1978). Cracks and fissures may develop and constitute further weak zones from which processes of mass movement start. These properties may therefore vary with texture (size of particles), mineral composition, moisture content, degree of consolidation and degree of uniformity (*Howard* and *Jahns* 1978).

5. Impact of SSOM on landscape development

All types of mining and quarrying, either at large or small scales, involve excavation of geomorphological and geological structures, which results directly or indirectly in a range of landforms. The three common categories of landforms resulting from anthropogeomorphic processes, according to *Jones* (2001), are as follows: human-made, human-induced and human-modified landforms. However, no study has yet identified those associated with the SSOM sector, which is why we strive in this section to summarize (*Fig. 4*) and describe hypothetical geomorphological features that could result from SSOM. This work is mostly based on field surveys conducted between 2008 and 2014 in the Great Lakes Region of Africa.

5.1 Human-made landforms

Human-made landforms are created deliberately for a specific purpose (*Jones* 2001), e.g., the removal of overburden material to exploit the underlying ore in the case of mining activities.

Several human-made landforms emerge as the direct and discernable consequence of excavation in the course of mining activities. They are mainly associated with pitting or trenching. **Pits** (in flat areas) and pit walls or **trenches** (on hillsides) are artificially created depressions (or negative landforms) in the ground. In places where intensive mining activity has occurred for many years, the landscape is completely potholed and covered in waste (*Crispin* 2003a). Some hillside mining locations may also feature lode mining, which generally develops from a pit wall. There might be a development of shallow **galleries** following the excavation of an ore-bearing vein. The roofs of galleries sometimes collapse and, as described above, create **sinkholes**, another human-induced landform. Sinkholes were identified at the Kivuvu mine in Burundi during a field research campaign in 2008.

A **pit wall** is an over-steepened slope that is prone to further landscape dynamics described in the next section. The stripped-off surface soil and tailings are more or less piled up in nearby overburden dumps, forming a corresponding positive landform to the excavation pits. These newly exposed waste deposits and steepened slopes are prone to further soil erosion and mass movement processes, which develop landforms induced by human activity, or human-induced landforms.

5.2 Human-induced landforms

Human-induced landforms emerge from natural processes and in places and times wholly dependent on anthropogenic activity (*Jones* 2001). In SSOM sites, geomorphic processes develop on mine pit walls, pits, waste piles or in their surroundings where the primary human-made landforms were created. This results in a range of geomorphological features, where **rills** formed by surface runoff on pit walls are the most identifiable. Piping is likely to play a significant role in the development of these features. Pipes are further enlarged with on-going erosion and develop to **gullies**, a process that can ultimately lead to the formation of badlands (*Byizigiro* and *Biryabarema* 2008). The disturbance produced by one slope failure often leads to the weakening of adjacent areas, particularly on the upper part of the backslope, resulting in the development of **cracks** that decrease shear or tensile strength and allow the entry of water into weakened zones between blocks (*Varnes* 1984). These weakened zones often constitute the plane for further mass movements from the summit of the pit. **Landslides** (rock slides or debris slides) along over steepened mine slopes result from shear-strain collapse and displacement along one or several surfaces that are visible or may reasonably be inferred (*Westerberg* 1999). Landslides themselves alter the geometry of the slopes, often unfavourably, by adding material to the base and creating steeper slopes at their heads (*Varnes* 1984).

The scar upslope of mine pits, from which the displaced material has been removed, constitutes a 'remaining landform' known as a 'crown' (*Westerberg* 1999). **Slumps** develop due to an accelerated undercutting process that is more active under the influence of running water, weakening the whole fabric of the regolith, which collapses in gradual landforms resembling stairs.

Topples are landforms that likely develop by the forward rotation movement of a unit of rock about a fixed base, below or low in the unit (*Alejano* et al. 2010). This forward rotation occurs under the action of gravity and forces exerted by adjacent units of rock or by fluid in the regolith (*Westerberg* 1999). A "**stack**" is a pillar of rock or regolith that has been isolated through the toppling process.

Less obvious, because it is hidden, is the effect of mass movements within masses of clay and shale (*Varnes* 1984). The shear strength of such deposits is profoundly affected by shear displacements, which within the zone of movement can transform a relatively disordered fabric into a highly oriented and weaker one (*Varnes* 1984). *Byizigiro* and *Biryabarema* (2008), however, found that this effect becomes stronger and more spectacular on walls of mine pits parallel to the foliation of shales that are eroded largely through dip-parallel sliding.

5.3 Human-modified landforms

Human-modified landforms emerge when the extent and/or rate of geomorphic processes is changed by human activity (*Jones* 2001). The main mechanism that triggers the formation of such landforms is a changed hydrological budget through the removal of protective plant cover or the exposure of excavated overburden material to erosion processes (*Jones* 2001). *Wilkinson* and *McElroy* (2007) estimated the global accumulation of alluvium resulting from such human activities. They reported that in higher-order tributary channels and floodplains, alluvium accumulation is one of the most important geomorphic processes in terms of sediment erosion and deposition worldwide, with an estimated mean rate of sediment accumulation in low-lying areas of ~ 12,600 m/m × y.

Mine tailings are often treated with slurry water (*Hossner* and *Hons* 1992), which is transported and deposited into dammed artificial ponds or natural depressions where the suspended particles settle out on the basis of size (*Murray* 1977). Larger, sand-sized particles settle near the pond inlet, while clay-sized particles settle at the pond outlet (*Murray* 1977). A general lack of structure is a common characteristic of mine tailings brought about by differences in texture (*Hossner* and *Hons* 1992). Debris '**tailing fans**' form downslope of the outlet of mines and can contribute to the deviation of stream courses, thus accelerating the undercutting of outer stream banks (*Byizigiro* and *Biryabarema* 2008). SSOM operations thus may indirectly result in lateral landslides or slumping along concave stream banks. The concave slopes are modified and may become steeper than the opposing convex slope (*Byizigiro* and *Biryabarema* 2008). Furthermore, debris flows spread downstream, often contributing to the formation of systems, which may result in a negative impact on potential land uses along the neighbouring floodplains. The above descriptions support *Goudie's* statement that through a lack of understanding of the operation of geomorphological systems, humans have deliberately and directly altered landforms and processes and have thereby caused a series of events that were neither anticipated nor desired (*Goudie* 2010).

6. Long-term impact of SSOM

It is recognized that mining activity, whether large- or small-scale, has the ability to substantially change the physical landscape and therefore has the potential to cause long-term environmental impacts (*Crispin* 2003a).

Long term-impacts of SSOM on geomorphological development were studied by *Raab* et al. (2010). They found that the onset of flood-loam deposition in the Lower Vils River Valley (Bavaria, Germany) coincides with the intensification of soil erosion on the valley slopes, which was triggered by mining-induced activities, especially by deforestation in combination with the transport of charcoal to the ironworks (*Raab* and *Völkel* 2005) during the late-medieval peak of ironworking activity in the region. *Higgitt* and *Lee* (2001) state that human activity in the British Isles during the last 1,000 years has had a considerable impact on landscape development, with (small-scale) mining activities contributing significantly to the human-induced landscape. *Busch* and *Maas* (2007) noted the risks associated with abandoned mines in Germany, namely the risk of collapse of subsurface cavities and opencast mine slopes.

The area of influence around such abandoned sites is defined as the area whose characteristics or functions are actually influenced by the former mining activities and the area where a future influence cannot be excluded (*Busch* and *Maas* 2007). *Nelson* and *Church* (2012) investigated the geomorphic impact of nineteenth century placer mining along the Fraser River, British Columbia, Canada, by estimating the volume and grain-size distribution of excavated sediment, evaluating the transport potential for the sediment in the river, and discussing the relationship between placer waste sediment and the observed morphodynamics of the Fraser River channel. The Gatumba area is a more recently investigated example of human-induced landform development around small-scale mine sites. In this mountainous area, the primary trigger for soil erosion on hillslopes is significantly accelerated by SSOM operations, which are conducted in close proximity to agricultural areas.

7. Summary and conclusion

Small-scale opencast mining (SSOM) is a prevalent economic sector in the developing countries of Africa, Asia, Oceania and Central and South America. It has become a major segment of the global mining industry with extensive grassroots effects on the national economies of the developing world. The negative impacts of SSOM have recently become a focus of research, involving a variety of scientific disciplines. Recommendations for improving legal, social, economic and environmental aspects of the subject have been formulated, but the assessment of geomorphologic impacts is yet to be considered in greater detail.

SSOM operations are often associated with adverse impacts on the environment, largely because of the extraction methods employed. Excavation operations are mainly associated with pitting and trenching and sometimes with the development of shallow galleries. These processes are associated with the comprehensive removal of the vegetative cover and overlaying soil and/or the removal of materials from shallow underground depths.

Due to the excavation, translocation and exposure of bare soil material, new geomorphic processes are initiated and naturally running processes are accelerated. This results in the emergence of specific geomorphic landforms and alters the natural development of landscapes. The most obvious erosive features include rills, gullies, slides, topples, slumps and sometimes sinkholes. Depositional features include debris flows and tailing fans that form at the outlets of mine pits and braided channels that develop downstream as a consequence of high sediment inputs. The extent of onsite landscape degradation and offsite impacts (mostly downslope and in low-lying alluvial plains) largely depends on the magnitude of the mining activity.

In most cases, the disturbed landscape is not properly, if at all, reclaimed. For instance, the removed topsoil, which would be essential for subsequent reclamation measures, is commonly not preserved. Given the increasing demand for arable land resulting from an ever-increasing population in developing countries, the development of adequate mitigation strategies using simple, low-tech and environmentally friendly reclamation techniques is becoming increasingly important. In-depth knowledge of the sensitivity of the natural landscape and specific geomorphic processes to the various types of SSOM operations is thus an essential prerequisite for developing efficient mitigation methods.

Acknowledgements

The study is supported by the German Academic Exchange Service (DAAD). We would like to thank Coltan Environmental Management 'CEM', a German project in Central Africa 2007-2014, for financial support of the field study. We thank *Lukas Freytag*, Brandenburg University of Technology Cottbus-Senftenberg, for his editing of the tables and figures in the first manuscript and the anonymous reviewers for their valuable comments on the manuscript.

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