

# **Geomorphic Processes Associated with Small-Scale Opencast Mining and Mitigation Measures: Case Study of the Gatumba Mining District in the Western Highlands of Rwanda**

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# **Geomorphologische Prozesse in Zusammenhang mit kleinskaligem Tagebau und Mitigationsmaßnahmen: Fallstudie des Gatumba-Bergbaugebiets im westlichen Hochland von Ruanda**

Von der Fakultät für Umweltwissenschaften und Verfahrenstechnik der Brandenburgischen Technischen Universität Cottbus-Senftenberg zur Erlangung des Akademischen Grades eines Doktors der Naturwissenschaften (Dr. rer. nat.) genehmigte Dissertation.

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## **Declaration**

I hereby declare that this doctoral dissertation is the result of my own research carried out at the Brandenburg University of Technology Cottbus-Senftenberg, Germany, within the framework of the International Graduate Program in Land Use and Water Management.

Professor Thomas Raab, Head Chair of Geopedology and Landscape Development of the Brandenburg University of Technology Cottbus-Senftenberg, Germany have been the main Supervisor of this research. Dr Thomas Maurer, Chair of Hydrology and Water Resources Management of the Brandenburg University of Technology Cottbus-Senftenberg, Germany, acted as Co-supervisor.

I hereby admit that this dissertation has never been submitted in whole or in part for a degree at the Brandenburg University of Technology Cottbus-Senftenberg, or elsewhere. References to other people's research have been duly cited and acknowledged in this research work accordingly.

Rutazuyaza Vaillant Byizigiro

## Summary

This thesis deals with geomorphic processes associated with Small-Scale Opencast Mining (SSOM) in the Gatumba sector of the Western Highlands of Rwanda. In this area tin and tantalum mining was carried out for decades, and it has brought about increase in the wealth and standard of living of the people. Though a lot has been done and achieved in soil erosion research, and despite the enormous wealth coming from mining in Rwanda and Gatumba sector in particular, the negative environmental impacts resulting from mining activities were overlooked by miners and stakeholders and are scarcely addressed in the research yet. This trend was bound to last since there were no valid guidelines for assessing impacts and reclamation of mine sites for the operators in the sector. It was recently, in 2007, that restoration of mining areas has received great attention from the Rwanda Geology and Mine Authority.

The objective of the research was to assess and to increase the understanding of geomorphic impact produced by SSOM. In this regards, the following aspects which indicate the types and spatial distribution of geomorphic processes were measured: (i) investigate the landforms typical of SSOM, (ii) map the watershed morphometry of the study area, (iii) analyse the most relevant properties of soils in term of geomorphology, and (iv) to assess the soil loss potential in the study area.

Primary and secondary data were collected from Government agencies and personal observations. Desk study to review papers and relevant literatures, field observation and experiments, laboratory analyses, mapping and modelling using RUSLE were combined together to develop a practical and integrated methodological approach to effect and realize the objectives. The argument guiding this analytical approach is that physical processes produced by mining cannot be assessed through a single method. The first step mainly concentrated on defining mining sites suitable for assessing geomorphic processes. Within the two studied mines, namely Ruhanga and Gatare, different plots were identified based on the post-mining land uses, to investigate the level of soil and landscape degradation by comparing them with that of control sites located outside of mining influence. Modelling using RUSLE in GIS interface enabled to quantify soil loss potential within the mines and the watershed.

Results indicate that the direct processes associated with opencast mining commonly involve pitting and trenching. Indirect and less conspicuous processes emerge as a long-term consequence of mining. They include depletion of organic matter, compaction or loosening of soil particles in mine sites mostly reflected by low content in organic matter, low rating in soil stable aggregates, and often high soil bulk densities which are variably distributed within the mine sites. This could explain the restriction or lowering, or the rapid infiltration of water into the soil during field experiments, as a consequence probably of the sealing

of soil pores or the formation of fissures around mine shafts, from which slides or slumps occur. In average, soil organic matter comprises between 1 and 2.5 % on control sites and ex-mine cultivated sites. organic matter content of soils on reclamation sites was in the same ranges with that of control and ex-mine cultivated sites, but could reach 4,8 % in topsoil of some sample locations. The ex-mine self-recovering sites present much lower organic matter content which doesn't exceed 2 % in general. The soil aggregation rating of the area is from very low (8%) to low ( $\leq 13.5$  %). In general, the bulk density ranges between 1.29 to 1.56 g cm<sup>-3</sup>, and locally can attain 1.76 g cm<sup>-3</sup>. As a consequence, the total porosity changes locally. Application of correlation and multiple regression models showed a strong influence of soil organic matter on the bulk density. Infiltration tests performed on different experimental sites showed differences of rates in water intake rates as in infiltration curves as well. Infiltration rates are variably distributed over the mines. They range from very slow (3.8 mm hr<sup>-1</sup>) to rapid (111.18 mm hr<sup>-1</sup>). Atterberg Limits analyses showed that soils of Gatumba Mining District do not possess extreme properties and they are suitable for engineering purposes. The liquid limit ranges between 51 % and 26 %, whereas the plastic limit is comprised between 22 % and 18 %. The highest plastic index (PI) determined was 29 % and the later soil had a plastic index of 6 %.

The average soil loss in the Gatumba watershed is 27.45 t ha<sup>-1</sup> yr<sup>-1</sup> with a standard deviation of 0.891. More than 65% of land are prone to high rates of soil loss (exceeding 10 t ha<sup>-1</sup> yr<sup>-1</sup>), and an increasing soil erosion follows increasing slope and land use patterns. The maxima of soil erosion rates are found in Upper Kibilira, Kirombozi and Gisuma catchments respectively. Based on different scenarios applied to quantify soil erosion rates, we found that more the organic matter content from 0. 5%, 2% and >2%) is increased with better support practice (from contour, strip and terrace), more the soil erosion potentials are decreased linearly, in the order of 18.8 to 17.8 t ha<sup>-1</sup> yr<sup>-1</sup> from 2% to >2 % of organic matter content respectively.

To make SSOM more environmentally sustainable, there is a need of developing integrated practices and cross-cutting approaches that reduce the environmental impact of mining operations, and leave mine sites in an acceptable state for reuse by people or systems. Practices such as isolation of soil and earth material, stabilization of slopes and amendments of sites to be restored should be highly considered in the process of rehabilitation of affected sites

**Key words:** Small-scale opencast mining, geomorphology, processes, landforms, mitigation strategies

## Zusammenfassung

Diese Arbeit behandelt geomorphologische Prozesse, die im Zusammenhang mit kleinräumigen Tagebauen (Small-Scale Opencast Mining) in der Gatumba-Region des westlichen Hochlands von Ruanda auftreten. In diesem Gebiet fand jahrzehntelanger Zinn- und Tantalabbau statt, der das Einkommen und den Lebensstandard der Bevölkerung erhöht hat. Obwohl im Bereich der Bodenerosionsforschung viel unternommen und erreicht wurde, und trotz des aus dem Bergbau in Ruanda und Gatumba kommenden enormen Reichtums, wurden dessen negative Auswirkungen auf die Umwelt sowohl von Bergbautreibenden als auch anderen Interessengruppen ignoriert und von der Forschung weitgehend vernachlässigt. Dieser Zustand hat sich verfestigt, da es für die Akteure in der Region keine verbindlichen Regelungen hinsichtlich Erfassung von Auswirkungen des Bergbaus und Wiederherstellungsmaßnahmen gibt. Erst kürzlich, im Jahr 2007, hat die Wiederherstellung der Bergbaugebiete größere Aufmerksamkeit seitens der Ruandischen Geologie- und Bergbaubehörde erhalten.

Das Ziel der Forschungsarbeiten war es, die geomorphologischen Auswirkungen von kleinräumigen Tagebauen abzuschätzen und besser zu verstehen. In diesem Zusammenhang wurden die folgenden Aspekte, die die Art und räumliche Verteilung von geomorphologischen Prozessen charakterisieren, erfasst: (i) Untersuchung der Landschaftsformen, die für SSOM kennzeichnend sind, (ii) Kartierung der Einzugsgebiets-Morphometrie im Untersuchungsgebiet, (iii) Analyse der relevantesten Bodeneigenschaften hinsichtlich der Geomorphologie, und (iv) Abschätzung der potentiellen Bodendegradation im Untersuchungsgebiet.

Primäre und sekundäre Daten wurden bei Regierungsbehörden und durch eigene Beobachtungen zusammengestellt. Literaturrecherche, Feldbeobachtungen und-experimente, Laboranalysen, Kartierung und Modellierung mittels RUSLE wurden kombiniert um einen praktischen und integrativen methodischen Ansatz für das Erreichen der Zielstellungen zu entwickeln. Die Grundidee bei diesem analytischen Ansatz ist, dass die mit dem Bergbau assoziierten physikalischen Prozesse nicht durch nur eine einzige Methode erfasst werden können. In einem ersten Schritt wurden geeignete Tagebaue für die Erfassung geomorphologischer Prozesse bestimmt. Innerhalb der zwei untersuchten Tagebaue (Ruhanga und Gatara) wurden anhand der nachbergbaulichen Landnutzung verschiedene Untersuchungsflächen identifiziert, um den Grad der Boden- und Landschaftsdegradierung anhand des Vergleichs mit Kontrollstandorten außerhalb des bergbaulichen Einflusses zu untersuchen. Modellierung mit RUSLE über ein ArcGIS-Interface ermöglichte die Quantifizierung des Bodenabtragspotentials innerhalb der Tagebaue und des Einzugsgebiets

Die Ergebnisse zeigen, dass die direkten Prozesse, die mit tagebaulichem Bergbau verbunden sind, üblicherweise die Anlage von Gruben und Gräben umfassen. Indirekte und weniger augenfällige Prozesse treten als langfristige Konsequenz des Bergbaus auf. Sie umfassen die Verringerung der organischen Substanz, Verdichtung oder Auflockerung von Bodenpartikeln an Bergbaustandorten, die meist mit einem niedrigen Gehalt an OS einhergeht, niedrige Gehalte an stabilen Bodenaggregaten, und oftmals hohen Lagerungsdichten, die variabel innerhalb der Bergbaustandorte verteilt sind. Dies könnte die Beschränkung oder Absenkung, oder die schnelle Infiltration von Wasser in den Boden während der Feldexperimente erklären, möglicherweise als Konsequenz der Porenversiegelung oder der Rissbildung um Minenschächte, von denen aus Rutschungen oder Grundbrüche entstehen. Die organischen Substanz-Gehalte reichen von 1 bis 2,5% an den Kontrollstandorten und landwirtschaftlich genutzten ehemaligen Bergbaustandorten. OS-Gehalte an wiederhergestellten Standorten waren in derselben Größenordnung wie die Kontrollstandorte und die landwirtschaftlich genutzten ehemaligen Bergbaustandorte. Die sich selbst erholenden Standorte im ehemaligen Tagebau weisen weit niedrigere organischen Substanz-Gehalte auf, die generell 2 % nicht überschreiten. Die Rate der Bodenaggregatbildung reicht von sehr gering (8 %) bis gering ( $\leq 13,5$  %). Die Lagerungsdichten reichen von 1,29 bis 1,59 g cm<sup>-3</sup>, und können lokal bis 1,76 g cm<sup>-3</sup> erreichen. Als Konsequenz ändert sich auch die Gesamtporosität lokal. Die Anwendung von Korrelations- und multiplen Regressionsmodellen ergab einen starken Einfluss der organischen Substanz auf die Lagerungsdichten. Infiltrationsexperimente, die an Proben der verschiedenen Versuchsstandorte durchgeführt wurden, zeigten Unterschiede sowohl bei der Wasseraufnahmerate als auch bei den Infiltrationskurven. Infiltrationskurven sind variabel über die Untersuchungsstandorte verteilt. Sie reichen von sehr langsam (3,8 mm h<sup>-1</sup>) bis schnell (111,2 mm h<sup>-1</sup>). Die Versuche zu den Atterberg'schen Grenzen zeigen, dass die Böden des Gatumba-Bergbaudistrikts keine extremen Eigenschaften aufweisen und für technische Maßnahmen geeignet sind. Die Fließgrenze liegt zwischen 26 % und 51 %, wohingegen die Ausrollgrenze Werte zwischen 18 % und 22 % umfasst. Die höchste gemessene Ausrollgrenze war 29 %, und dieser Boden wies eine Plastizitätszahl von 6 % auf.

Der durchschnittliche Bodenabtrag im Gatumba Einzugsgebiet beträgt 27,45 t ha<sup>-1</sup> a<sup>-1</sup> mit einer Standardabweichung von 0,891. Mehr als 65 % des Landes sind anfällig für hohe Bodenabtragsraten (mehr als 10 t ha<sup>-1</sup> a<sup>-1</sup>), und eine steigende Bodenerosion folgt steigenden Hangneigungen und Landnutzungsmustern. Die Höchstwerte der Bodenabtragungsraten finden sich jeweils im Oberen Kibilira, Kirombozi und Gisuma-Einzugsgebiet. Auf Grundlage verschiedener Szenarien, die zur Quantifizierung der Bodenerosionsraten angewendet wurden, zeigte sich, dass mit höheren organischen Substanz-Gehalten (2 % bis >2 %) und mit verbesserten Anbaupraktiken (Kontur-, Streifen-,

Terrassenanbau) die Bodenerosionsraten linear in der Größenordnung von 17,8 bis 18,8 t ha<sup>-1</sup> a<sup>-1</sup> verringern.

Um kleinräumigen Tagebauen umweltverträglicher zu gestalten bedarf es der Entwicklung integrierter Methoden und interdisziplinärer Ansätze die die Umweltfolgen von Bergbauoperationen reduzieren und Bergbaustandorte in einem nutzungsfähigen Zustand hinterlassen. Praktiken wie die Trennung von Boden und Gesteinsaushub, die Stabilisierung von Hängen und die Verbesserung von Wiederherstellungsstandorten sollten größte Berücksichtigung beim Rehabilitationsprozess betroffener Standorte finden.

**Schlüsselworte:** kleinräumige, Tagebaue, Geomorphologie, Prozesse, Landformen, Schadensminderungsmaßnahmen



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## List of Abbreviations

ALUC: Agricultural Land Use Consolidation

A&SM: Artisanal and Small-scale Mining

BD: Bulk density

CARIM: China Australia Research Institute for Mine waste Management

CASM: Community and Small-scale Mining

CEC: Cation Exchange Capacity

CEM: Coltan Environmental Management

CIP: Crop Intensification Programme

CNWD: Congo-Nile Watershed Divide

COREM: Compagnie de Recherche et d'Exploitation Minière

CP: Ex-mine cultivated site

CS: Control Site

CSIRO: Commonwealth Scientific and Industrial Research Organization

DEM: Digital Elevation Model

EIA: Environmental Impact Assessment

ERS : Ex-mine reclamation site

FAO: Food and Agriculture Organization of the United Nations

GEORWANDA: Compagnie Géologique et Minière du Rwanda

GDP: Gross Domestic Product

GIS: Geographical Information System

GMC: Gatumba Mining Concession

GPS: Global Positioning System

IR: Infiltration rate

LL: Liquid Limit

MINETAIN: Société des Mines d'Étain du Ruanda-Urundi

MMSD: Mining, Minerals and Sustainable Development

NMC: Natural Moisture Content

NRCS: Natural Resources Conservation System

OMAFRA: Ontario Ministry of Agriculture, Food and Rural Affairs

OM: Organic Matter content

PAWC: Plant Available Water-holding Capacity

PI: Plasticity Index

PL: Plastic Limit

PWP: Permanent Wilt Point

REDEMI: Régie d'Exploitation et de Développement des Mines

RS: Remote Sensing

ERS: Ex-mine reclamation site

RUSLE: Revised Universal Soil Equation

SADC: Southern African Development Community

SAMUKI: Société Minière de Muhinga et de Kigali

SOMIRWA: Société Minière du Rwanda

SR: Ex-mine self-recovering site

SSOM: Small-Scale Opencast Mining

USAEWES: United States Army Engineers Waterways Experimental Station

USDA: United States Department of Agriculture

US-EPA: United States Environmental Protection Agency

USLE: Universal Soil Loss Equation

WHC: Water Holding Capacity

WI: Water Intake

WMO: World Meteorology Organization

# 1 Introduction

## 1.1 Problem statement

Artisanal and Small-Scale Mining (A&SM) is a growing economic sector in many third-world countries, contributing significantly to local employment, foreign exchange earnings, and national gross domestic product (GDP) (Hilson, 2002a; Sousa et al., 2010; Buxton, 2013; Dorner et al., 2012). 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), where the overburden is stripped from the surface to expose the ore (Byizigiro et al., 2015).

Although mining contributes positively to the welfare on local populations, several discourses claim however the sector to be responsible of decline in agricultural and marine resources, e.g. loss of arable lands, and siltation of streams. Rapid relocation of earth material (e.g. pitting, trenching) and soil is conspicuous and direct geomorphic processes that affect mining sites. The magnitude of translocation of eroded soils may occur in connection with extreme rainfall. Long term indirect processes resulting from SSOM include landslides and rill development in perimeters being mined, but further and less discernible are degradation of soil and regolith properties. Depletion of organic matter (OM), compaction or loosening of soil particles in mine sites mostly reflected by low content in OM, low rating in soil stable aggregates (SSA), and soil bulk densities (BD) which are variably distributed within the mine sites, could be responsible of sealing of soil pores, formation of subsoil structures or fissures around mine shafts. These impacts severely affect the properties of soils which (1) promote the root growth, (2) accept, hold and supply water, (3) hold, supply, and cycle mineral nutrients; (4) promote optimum gas exchange, (5) promote biological activity, and (6) accept, hold and release carbon (Burger & Kelting, 1999; Byizigiro et al., 2015). 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 that adequate reclamation measures are almost never applied (Mallo, 2012; Byizigiro et al., 2015).

Gatumba area is one of the sectors of Rwanda which are highly mineralized in tantalum and tin ores, exploited over decades. Most of the ancient quarries remained as they were left by the former mining companies (1930-1985). Remediation was not carried out because leases were (and are still) upright and protecting the right to take up mining at any time (Byizigiro & Biryabarema, 2008). Quartz boulders and smaller fragments down to sand size form the bulk of the waste rock left behind. Bottoms of stream

valleys adjacent to mines were buried by this mass of loose sediment. Stream gradients were locally changed. After this period of major mining-related geomorphic processes, relatively subtle changes took place in and around the former quarries. The mined area exhibits geomorphic features on scars as well as on waste deposits.

In this densely populated area, high annual precipitation (1376 mm) and steepened topography (26°) constitute potentially the major natural factors influencing geomorphic processes, beside agriculture and mining which are regarded as aggravating anthropogenic factors (Byizigiro & Biryabarema, 2008). Westerberg (1999) highlights the vulnerability of farmers of densely populated areas subjected to mass movement. He stresses that, owing to the small-scale farming pattern, minor mass movements may deprive farmers of significant lands of their field. Having had substantial parts of their resource ruined, subsistence and cash crop farmers may potentially end up in an evil circle (Westerberg, 1999).

For research on tin and tantalum mining induced processes and mitigation, the Gatumba area is remarkably well suited. It exhibits the post-mining evolution at a stage about 30 years after mining stopped on extensive portions of mine sites. In view of this, it was paramount to investigate the geomorphic problems caused by SSOM. As several approaches could be used for this research, it was very important to estimate through the field study and laboratory analysis the level of soil degradation, to map and assess soil erosion risks using GIS-RUSLE based model within the study area.

## **1.2 Background and rationale of the study**

The geological and mineralogical studies for Rwanda started with the visit of the German Duke Mecklenburg during 1907. Between 1922 and 1923, a Belgian scientific expedition conducted by Reverend Canon Achille Salée and Delhayé provided necessary data for the compilation of the first geological map of Rwanda and Burundi at a scale of 1: 200,000. Special investigation on mineral resources potential in the eastern and western region of Rwanda and Burundi started in 1926 (Nsekaliye, 1978).

In the Gatumba sector, mining activities started in 1930's. Although many mining companies existed in Rwanda, the most renown operating in the Gatumba region are respectively the Ruanda-Urundi Tin Mines Company (Société des Mines d'Étain du Ruanda-Urundi, MINETAÏN, created in 1930), the Société Minière du Rwanda (SOMIRWA), a public mining company adopted in 1973, the 'Régie d'Exploitation et de Développement des Mines' (REDEMI), a government owned company established in 1989 respectively.

Throughout the literature, it appears that mining strategies, purely growth-led has turned out to be environmentally detrimental. Although the sector contributed positively to the welfare of local communities and national economies, the chances of building scientific how-to-do precautionary and mitigation strategies was seriously undermined and seemed to have not been a priority.

After the war and the genocide of 1994, the mining sector gained a strong support from the Government. In 2007, the Rwanda Geology and Mines Authority (RGMA), the actual Geology and Mines Department (GMD) was created to take over the activities of REDEMI. In the same period, the Government privatized the mining industry. The Gatumba mining concessions of western Rwanda were acquired by a private company, the Gatumba Mining Concession (GMC), a joint venture between the Government and a consortium of private companies. The recent reforms of the mining aimed at supporting and giving new focus “green mining”, to transform the sector into an industrial enterprise, to increase productivity, to prevent resulting impacts on humans and environment but also to remediate the previous impact produced by mining operation (Rukazambuga, 2008). In 2007, RGMA in partnership with Coltan Environmental Management (CEM), a German project, launched a research on mining in the Gatumba District to assess their impact. After a pilot phase in 2007–2008, the Volkswagen Foundation in 2010–2014 granted expertise and funds for a multidisciplinary and multinational research, to extend the project to other countries of the Great Lakes Region of Central Africa and researchers from Burundi, DR-Congo and Uganda were included. The aim was to assess the environmental impact caused by tin and tantalum mining in the region and to develop suitable re-cultivation strategies.

Geomorphic impacts produced by small-scale mining deserve more assessment, because it is one of the keys for land reclamation. This study was paramount because it opens a new and relevant research field for factors and processes associated with SSOM. More specifically (i) interrelations between human practices, in this case mining and natural conditions whose normal functionality is actually interfered are discussed, and (ii) the geomorphic landforms characterising SSOM sites as a product of human-induced landscape evolution are presented.

Since no previous research was carried out on this field, this thesis will be the first investigation that explores geomorphic processes associated with SSOM and their impacts in Rwanda, and comprehensively discusses both the natural aspects (e.g. slope, climate, etc.) of the highlands as a geomorphic system and the human factors that contribute to land disturbance and physical degradation of the area.

### 1.3 Motivation of the research

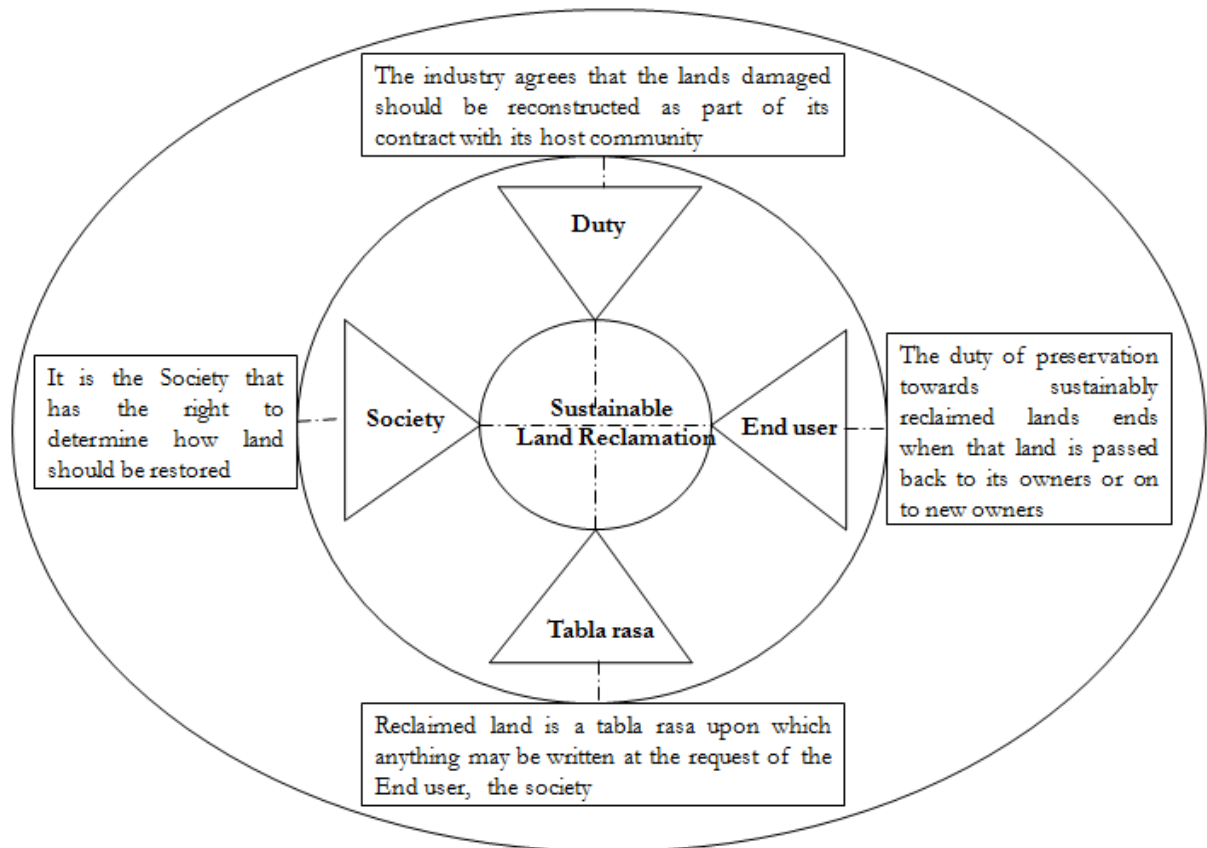
Mining without an impact on environment and inhabitants of the mine's surroundings is impossible. In the past, the wealth created by mines was of the first importance, while their impact on people and environment was hardly noticed. Today there are many mining operations that create an enriched landscape. Opencast pits hold beautiful new landscape and hard rock mines and quarries grow into ecosystems that are rare islands of nature in a sea of human occupation" (Rukazambuga, 2008). As effects of mining are worldwide known, many attempts were done by industrial mining to serve as base line from which mitigation measures can be decided (Yarbrough, 1983). Terms of references put forward by most researches were or are to study mining impacts with the aim of investigating process intensity in a specialized way (i.e. water pollution, soil fertility) which is principal in order to obtain a comprehensive understanding of any mining impact assessment topic. Others have explained in details the close relationship between mining activities and geology. In developed countries where the program of rehabilitation is successfully integrated at each stage of mining, several researches focus now on the late stage of evolution of these sciences, whether or not the visual perception of rehabilitated landscape satisfies local communities (Dávid, 2010).

In many developing countries, mining sector is a substantial source of income for local communities and governments as well. However, besides few initiatives in the area of environmental impact assessment and re-cultivation, e.g. CEM in central Africa (Rukazambuga, 2008), no real effort has been done to move the small-scale mining industry towards more sustainable development (Freak, 1998), specifically to assess geomorphic processes arising from SSOM sites in sub-Saharan developing countries.

Several authors underscore the ethical foundation of sustainable land reclamation in such a way related schools were created. Haigh (2000) described ethics of schools of sustainable land reclamation thinking within the surface mining enterprise, which are mainly built on four foundations as it can be seen in (Figure 1) below. He stresses that the reclamation of man-disturbed lands is not only a duty in the perspective of making the sector more sustainable, but requires various and complementary skills, where the society holds a pivotal role in determining post mining land uses. However, there might be flexibility in terms of final alternative decision on behalf of experts.

This study intends to identify factors and processes associated with SSOM, which is an essential contribution towards the sustainability of the sector and, at the same time, it accounts for the influence of the sector on land use potentials. For this an exploratory approach was used to provide a background for future in-depth studies. Westerberg (1999) argues that the broad geographical approach lends itself well to

a problem where the causal factors may be sought in both the natural and the human environment. This approach is compulsory to obtain not only a better understanding of how human activities and natural condition interact but also to help in identifying areas which deserve more detailed and specialized studies.



**Figure 1:** Ethical foundation of sustainable land reclamation (modified from Haigh, 2000)

It is expected that this thesis will analyse some aspects of direct relevance to geomorphic processes occurrence in SSOM sites such as the description of direct processes and associated landforms, assessment of physical properties of soils, mapping and modelling soil erosion risks in the study area. In the recommendations, mostly based on results, the study provides a framework to improve the collaboration between different stakeholders in the SSOM system, since a single expertise cannot be sufficient. Most of sections constituting the thesis can be read separately, since they describe separate sub-themes; a full picture, however, emerges if all chapters are read in a consecutive order.

## 1.4 Objective, research questions and hypotheses

Surface mining typically generate a considerable number of environmental impacts among which, landscape alteration remains one of the most conspicuous as stated by Dentoni (2012), and soil degradation which is particularly important in densely populated regions of developing countries that experience land shortages (Freak, 1998; Biryabarema et al., 2008). The research highlights the need to

consider specific geomorphic processes arising from SSOM, as a long-term problem on other natural resources. This would increase awareness to scientists and decision makers, so that they become more involved in attempts to recover and recommission abandoned SSOM sites for new uses, but also to move the sector in a new era of making it more sustainable.

The main objectives of the study was to (i) identify through field survey geomorphic landforms associated with SSOM, (ii) to assess through field and laboratory analyses and modelling typical processes and soil loss potential. Comprehensively the overall goal is to assess the natural and anthropogenic processes of land evolution and to recommend suitable mitigation techniques of geomorphic processes based on the results.

In order to assess and to increase the understanding of impact produced by SSOM, the field and laboratory analyses and soil loss modelling approaches enabled to (i) summarize arising hypothetical landforms, (ii) identify geomorphic processes triggered or the most altered by SSOM, and (iii) identify the spatial distribution of soil erosion potential in the study area.

In order to address the main issues raised in Section 1.1, the following research questions were formulated based on the specific objectives mentioned above:

- Are there geomorphic processes triggered by SSOM activities?
- Does SSOM have impacts on natural geomorphic processes?
- Do these geomorphic processes influence land use potentials?

The assumption is that operations involving SSOM in the study area have resulted locally in formation of degradation geomorphic landforms and alteration of land use quality. These could be regarded as the consequences of alteration of natural processes caused directly or indirectly by human interference, which in this context is considered as aggravating factor of geomorphic processes. The testable hypotheses for this research are formulated as follows:

- SSOM may alter or accelerate the natural geomorphic processes
- There are development of geomorphic landforms specific of SSOM
- The understanding of processes and landscape alterations may lead to improved mitigation strategies to prevent further land degradation



## **2 Factors and processes controlling geomorphological development in SSOM sites: A review**

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### **Abstract**

Artisanal and Small-Scale Mining (A&SM) is a growing economic sector in many third-world countries. This review focuses on 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 geomorphic processes, such as weathering, erosion, transport and deposition. By initiating new and modifying natural geomorphic processes, SSOM mining 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 only addressed in the current research. 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.

### **2.1 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, 2002a). A&SM refers to mining by individuals, groups, families or small cooperatives with minimal or no mechanization (Dreschler, 2001; Sousa et al., 2010). A&SM is therefore very labour-intensive, conducted by manual operations based on locally made tools like picks, shovels and

basins, etc. thereby, small capacity of machinery is employed (Dorner et al., 2012; Lahiri-Dutt, 2003). Such mining activities are usually confined to deposits which 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), where the overburden is stripped from the surface to expose the ore. As opposed to industrial large-scale opencast mining, SSOM uses no or less sophisticated machinery, and mostly semi-skilled workers, but also has significantly lower requirements in terms of implementation time and initial investment (Hilson, 2002b).

About 30 million people worldwide are employed directly and indirectly in such 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). 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 (Mirekugyimah & Soglo, 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). SSOM is therefore recognized to be the most widespread mining operation practiced in developing countries, where population is increasing at a higher rate in comparison with 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 (Heemskerk, 2005). Hilson and Garforth (2012) argue that agricultural poverty, or hardship induced by an over-dependency on farming for survival, has fuelled the recent rapid expansion of A&SM operations, e.g. throughout 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 that adequate reclamation measures are almost never applied (Mallo, 2012).

Recent studies highlighted the capability of SSOM activities for landscape change and geomorphic processes with low-intense research. Among the most significant geomorphic impacts are landforms alterations and accelerated soil erosion (Dentoni & Massacci, 2012; Hooke, 1999). 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 of 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. Removal of overburden material and formation of tailing heaps alter hillslope stability (Kainthola et al., 2011). Furthermore, soil properties are affected and their functionality undergoes alteration such as depletion of organic matter and nutrients, weakening of soil aggregates and compaction, among others. According to Burger and Kelting (1999), these impacts severely affect the properties of soils which (1) promote the root growth, (2) accept, hold and supply water, (3) hold, supply, and cycle mineral nutrients; (4) promote optimum gas exchange, (5) promote biological activity, and (6) accept, hold and release carbon. In consequence, the allocation of easily erodible material by tailings or landslides often results in increased stream siltation, turbidity of large drainage systems and sediment yield to streams (Sousa et al., 2010). Given that 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 (Lottermozer, 2003; Aubynn, 2009). As a great number of these activities are difficult to impede, small-scale mining activities may become even more environmentally destructive in the future (Hilson, 2003) and constitute threats to the long-term viability of effective land use and agriculture in affected areas.

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 deal with the specific environmental problems arising from A&SM, brings about according to (Zhang et al., 2011) a “grow first, clean up later” mentality, mainly in developing countries. Several projects to enhance the environmental awareness in developing and threshold countries were launched in recent years; e.g. 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 with the purpose of developing science-based, but tangible ‘how-to-do’ pre-cautionary and mitigation strategies (Freak, 1998). Operating independently on different continents, both projects address the same problem. As arable land in densely populated regions of Africa (Rukazambuga, 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 the focus on sustainable post mining agricultural land use (Freak, 1998; Rukazambuga, 2008). Along the same line, 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 international scientific debates discussed the best approaches for sustainable management of natural resources, particularly to avoid causes of ongoing degradation and loss of fertile soils. They all assert that the resources and by-products of soil and waste are all interconnected and have dependent relationships with one another, thus forming a nexus (Lawford, 2015). Soil being one of non-renewable natural resources that is often severely impacted by SSOM, all debates call for urgent broad adoption of sustainable land management practices in areas affected by anthropogenic activities (Bradshaw & Borchers, 2000; Donahue & Miller, 1990). 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 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 (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 geomorphic 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 the synopsis of the available relevant studies.

## **2.2 Global significance of SSOM as a potential geomorphic agent**

SSOM is one of 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.

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 developing countries, where approximately 90% of mines are small-scale operations (Ghose, 2003b; 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, 2003c). 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.

**Table 1:** Wastes and derelict lands resulting from SSOM in several developing regions

Country	Waste production/derelict	Reference
Malaysia	200,000 ha tin derelict	Hossner and Hons (1992)
Brazilian Amazon	SSOM moves more than 4 million m <sup>3</sup> 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	Heemkerk and Van der Kooye (2003)
Nigeria	321 sq.km affected by opencast mine wastes	Hossner and Hons (1992)
Himalayan region of India	More than 60% of land covered by mine wastes	Ghose (2003)
Zimbabwe	4,600 km of riverbeds are worked by 200,000 small-scale miners	Lombe (2003)

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 & Ouboter, 2004; 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).

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 & Gunson , 2006).

**Table 2:** Classification of Small-scale mines based on annual mining output (t ha<sup>-1</sup>)

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 and LSM: Large-Scale Mine  
Source: (Ziran, 2003).

**Table 3:** Classification of mining scales for selected minerals in China (t yr<sup>-1</sup>)

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

Source: (Shen & Gunson , 2006; Ziran, 2003)

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 60,000 tonnes of ore per annum would be considered a small mine. Those ranging between 300,000 and 900,000 tonnes per year are “medium-scale”, and those with a production exceeding 900,000 tonnes per year are “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.

## 2.3 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 geomorphic impact. A synopsis of the common grades of technology and organization involved in SSOM operations is provided in Figure 2. 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, 1991; Bugnosen, 2003; Dreschler, 2001)
- (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 (Sottemeister et al., 2002). Attempts were undertaken to place SSOM into categories: ‘artisanal’, ‘traditional small-scale’ and ‘advanced small-scale’ (Kambani, 1995; Masialeti & Kinabo, 2003; Hentschel et al., 2003), based on ‘grades of technology’ and organization characterizing the sector.

### 2.3.1 Grades of technology within SSOM

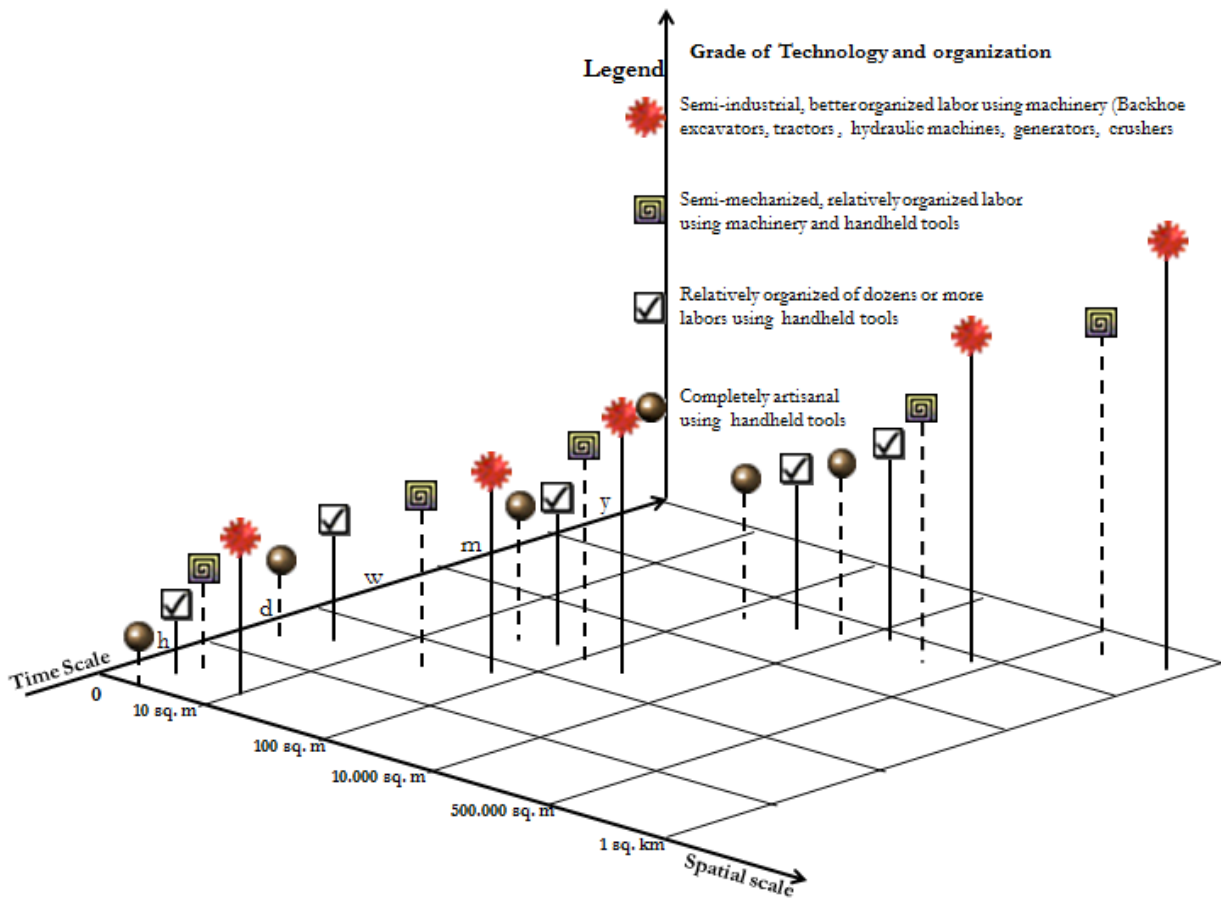
- (i) **Artisanal mining** refers to the smallest and simplest of operations. These operations feature simple tools and are informal business enterprises. They can take the form of spontaneous practice without title to property as well as activities with a registered claim to the land plot. Artisanal mining is predominantly perpetuated by illegal miners known, “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 **Advanced 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, SSOM workers 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 (Heemkerk, 2005).

The three dimensional figure below 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.



**Figure 2:** Grade of technology of SSOM– organization and potential intensities regarding geomorphic processes (Byizigiro et al., 2015)



This is a speculative thinking that can serve as a baseline from which further investigation of the impacts of individual techniques could 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.

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, 2001; Hilson, 2002b) Figure 3).

### 2.3.2 Extraction methods

The extraction methods described here are related to mining processes that are described further, along with geomorphic factors, in the following sections. These methods are regarded as anthropogenic processes. They 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) (Figure 3A). (ii) **Deep alluvial mining** involves the extraction of deep alluvial deposits from the banks of 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) (Figure 3B) 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 (Figure 3C).

However, the level of technology does not allow mining of ore at great depths. Access via shafts generally involves old metal structures and through 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).

### 2.3.3 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 19<sup>th</sup> century (Nelson & Church, 2012), are mostly based on sluicing, which is a trapping mechanism captures particles of heavy minerals through the use of sluices.

Three basic applications are known:

(i) With simple **sluicing**, ore-bearing sediment is shovelled into sluice boxes (Figure 3D). (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<sup>3</sup> of alluvial ore per hour (Veiga et al., 2006).



**Figure 3:** Techniques and methods associated with SSOM

A. Shallow alluvial mining. B. Deep alluvial mining (Chirico & 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 in Gatumba, Rwanda. I. Hydraulic mining (Heemkerk, 2005). Apart from B, D, F and I, all other photos were taken in Ruhanga and Nkokwe mines, Gatumba Mining District, Rwanda (Photographs taken between 2008 and 2014 by the Author).

(ii) In **ground sluicing** (Figure 3E), a stream is diverted to erode material that is then flushed into a sluice channel (Cuadra & 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). Panning using plastic tray with riffles (Figure 3F) can be used by giving the Pan several vigorous shakes back and forth and from side to side, but not too vigorous to wash material out of the Pan. In the Gatumba Mining District (Rwanda), semi-machinery using bulldozers and electrical shaking tables (Figure 3G-H) is sometimes used on localised sites. Although the impression is a more or less advanced technique, the machinery is however limited to mining and never used during pre-mining or post-mining phases.

(iii) In **hydraulic mining** (Figure 3I) high-pressure water is sprayed against the walls of a mine to excavate sediments. Water is redirected into 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** or **panning**, or both together (Figure 3E-F) (Veiga et al., 2006). Panning, as described so far, 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: 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 lack of storage facilities (Tarras-Wahlberg, 2002), these operations may have a significant impact on local geomorphic processes.

## 2.4 Natural and anthropogenic impacts on the geomorphology of SSOM sites

Geomorphic processes in SSOM sites are controlled by direct anthropogenic intervention and natural factors. The presence of both was 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.

### 2.4.1 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 process 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 Information Services, 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 (Sottemeister et al., 2002).

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.

Specifically for SSOM, table 5 below 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 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 4:** Activities involved in SSOM versus LSOM(modified from Asiedu,2013)

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

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).

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 equilibrium after 200 to 400 years (Holmberg,

1983), whereas other properties, such as the distribution of  $\text{CaCO}_3$ , may require as much as 1,000 years reaching the point where they resemble native soils (Schaaf & Hüttl, 2005).

**Table 5:** Geomorphic processes and outcomes in SSOM sites (modified from Goudie, 2006; Dávid, 2010)

Direct SSOM Processes		
Excavation	Construction	Hydrological interference
Cutting and striping vegetation, digging ditches, pitting, trenching, shallow tunnelling	Tailings dam, mine waste piles, rock dump, 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

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

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

#### 2.4.2 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 topsoil 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.

The natural factors that control the geomorphic processes in SSOM sites (or surface mine sites in general) are mainly (i) the climate (e.g., precipitation and the intensity of single-weather events) (Ruiz-Jaen & Aide, 2005), (ii) the topography (i.e., the slope length and gradient, which govern water and sediment transfer)

(iii) the geology (i.e., the streambed or underlying parent material, which controls flows and stream dynamics, such as lateral or vertical incision) (James, 2004), (iv) the slope regolith (stability of which largely depends on the nature of the parental material and the slope gradient) (Kirkby, 1980), (v) and the vegetation cover (which, as a stabilizing factor, governs soil loss and mass movements) (Craul & Rowe, 2008). High-intensity mining operations, involving for instance large tracks of deforestation and trenching within soil masses, significantly impact the environment and soils and accelerate natural geomorphic processes (Parrotta & Knowless, 2001). These accelerated processes include slope collapse, mass movement, soil erosion, and alterations in soil physical properties, such as shear strength and infiltration capacity (Toy et al., 2002). Sediment mobilization affects downslope areas, which may become covered by debris and colluviums (Byizigirow & Biryabarema, 2008). Rumsby (2001) states that the production of sediment through anthropogenic processes generates a supply that can be transferred from slopes to channels, and transported through rivers to coast. With respect to SSOM, the above statement implies that (i) mining, even if restricted to a relatively small area, can potentially affect larger and more remote areas through slope collapse, sediment translocation and stream contamination, and (ii) associated operations are often a catalyst for natural geomorphic processes, resulting in the formation of various landforms. Flow processes separate fine and coarse particles, and the fine particles are transported farther downstream, resulting in a longitudinal sorting of material, where particle sizes are a proxy for the distance from the location of the mining site (Byizigirow & Biryabarema, 2008).

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, 2003c). Yarbrough (1983) defines subsidence as “the lowering of the strata, including the surface due to underground excavation” that results in **sinkhole** landforms.

Normally, **sinkholes** are landforms typically associated with industrial underground mining. The study of Harnischmacher and Zepp (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 & 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 on the landscape, and the highest subsidence value amounted to more than 25 m (Harnischmacher & Zepp, 2014). This type of landform, which was not directly discernible 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 & 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. Yilmaz 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 fall outs 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 & 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 & Jahns, 1978).

## **2.5 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 groups of landforms resulting from mining processes are, according to Jones (2001), human-made, human-induced and human-modified landforms. Based on Jones' major categorization, hypothetical landforms identified on SSOM sites during the field survey are summarized (Figure 4) and described in the following sections.

### **2.5.1 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

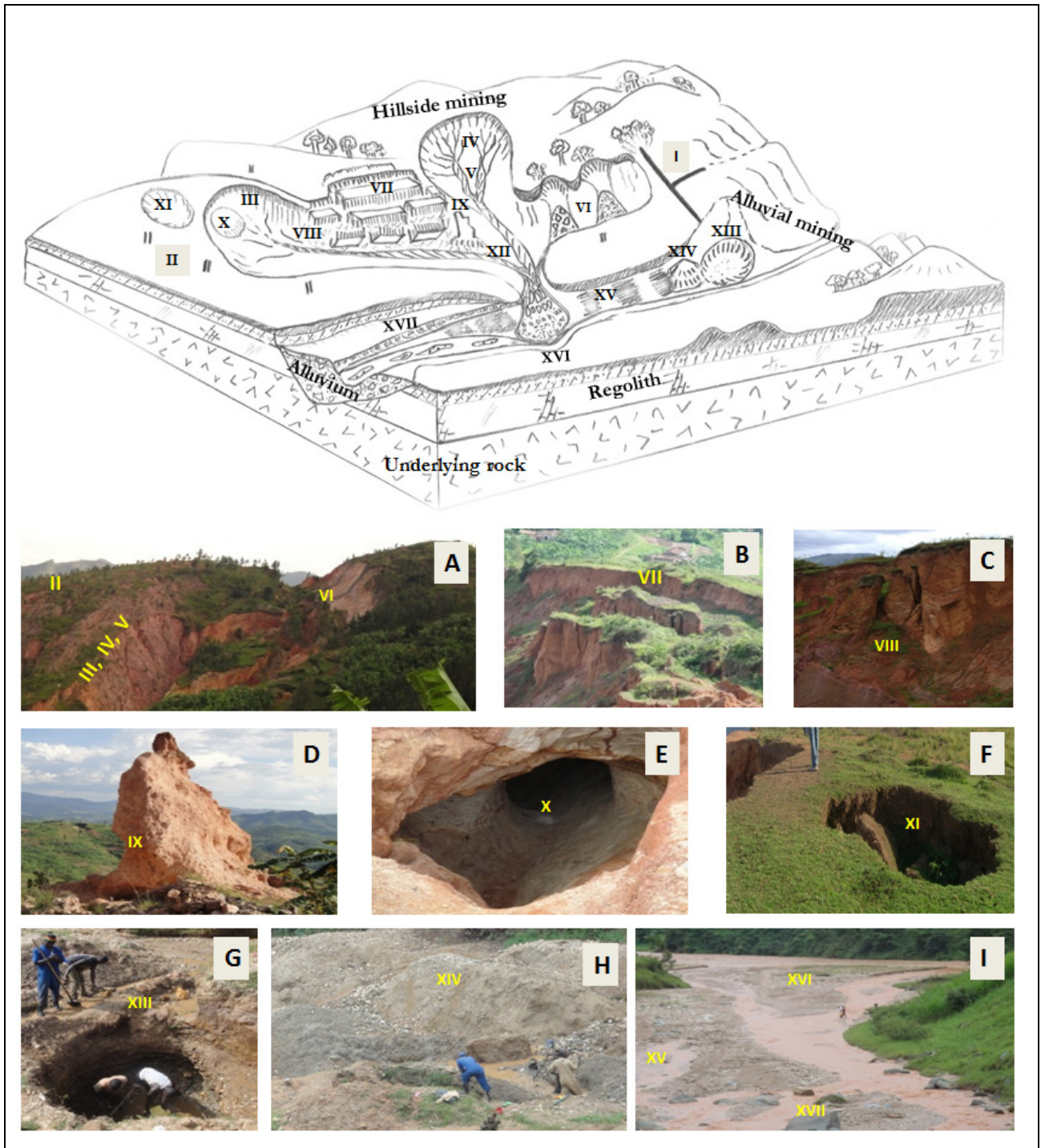
landforms emerge as the direct and discernible consequence of excavation in the course of mining activities. They are mainly associated with pitting or trenching. **Pits** (in flat areas) and pit walls or **trenches** (on hillsides) are artificially created depressions (or negative landforms) in the ground. In places where intensive mining activity has occurred for many years, the landscape is completely potholed and covered in waste (Crispin, 2003). 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.

### 2.5.2 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 & Biryabarema, 2008).

The disturbance produced by one slope failure often leads to the weakening of adjacent areas, particularly on the upper part of the back-slope, 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.



**Figure 4:** Overview of hypothetical landforms resulting from SSOM impacts (labels apply to both the 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 Tailing dump, XV Debris flow, XVI Tailing fan, XVII Braided stream channel. Photos were taken in Kivuvu mine, Burundi (xi) and Gatumba, Rwanda (Photographs taken between 2008 and 2014 by the Author).

**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.

### 2.5.3 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 translocation and deposition worldwide, with an estimated mean rate of sediment accumulation in low-lying areas of  $\sim 12,600 \text{ mm yr}^{-1}$ .

Mine tailings are often treated with slurry water (Hossner & 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 & 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 (Hossner & Hons, 1992). 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 & Biryabarema, 2008). Furthermore, debris flows spread downstream, often contributing to the formation of **braided stream channel** 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, 2006).

## **2.6 Long-term impact of SSOM**

Mining activity, whether large or small scale, has the ability to substantially change the physical landscape, therefore has the potential to cause long-term environmental impacts (Crispin, 2003). Studies show that mining has long term-impacts on geomorphic development (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 & Völke, 2005) during the late-medieval peak of ironworking activity in the region. Higgitt et al. (2001) states 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. Wolfgang and Klaus (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 (Wolfgang & Klaus, 2007). The geomorphic impact of nineteenth century placer mining along the Fraser River, British Columbia, Canada, was investigated 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 (Nelson & Church, 2012). 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.

## 3 Material and Methods

### 3.1 Gatumba Mining District

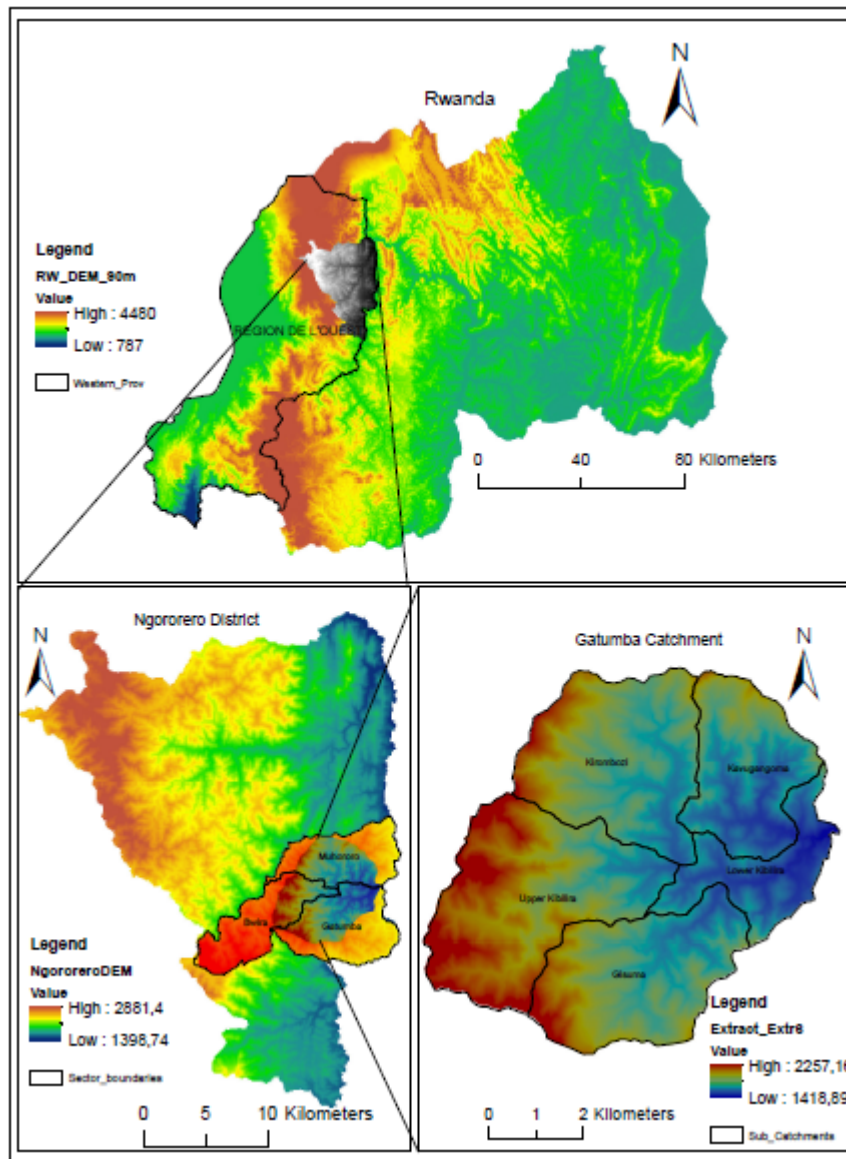
#### 3.1.1 Location of the study area

The Gatumba Mining Area is located in the Ngororero District in the Western Province of Rwanda, about 50 km west of Kigali. The geographic coordinates bounding this study area are 1°53'0" and 1°56'0" of south latitude and 29°37' 0" and 29°41' 0" of east longitude. The selected mines are located within a small watershed at the intersection of three sectors, namely Muhororo, Bwira and Gatumba border (Figure 5). Gatumba is one of the most important mining areas in Rwanda. It has procured its status as high-potential area owing to the presence of cassiterite (tin ore), niobo-tantalite (tantalum and niobium ore, locally called coltan), wolfram (tungsten ore), tourmaline and several other secondary minerals. In this study, the densely populated area has received great attention due to both intensification of mining and agriculture.

#### 3.1.2 Geology and mineralogy

Many researchers have surveyed the geology of central Africa (Peeters, 1956; Steenstra, 1967; Lehmann et al., 2008; Rumvegeri, 1991); others have specifically explored the geology and mineralogy of Rwanda (Varlamoff, 1961; Baudet et al., 1988; Baudin, 1979), and Gatumba District (Dewaele et al., 2011; Gérards, 1965; Bertossa, 1965). Information from these studies converges to point out the particularity of the Gatumba area.

The study area is an integral part of the Kibaran orogen which consists dominantly of Paleo and Mesoproterozoic rocks that have been intruded by different generations of granites (Dewaele et al., 2008). Recent studies indicate however the presence of two main granite generations in the Kibaran orogen (Kivu, Rwanda and Burundi):(i) G1-3 intruded the Paleo–and Mesoproterozoic rocks at  $1380 \pm 10$  Ma (U-Pb SHRIMP zircon)(Dewaele et al., 2007). The crystallisation of these granites did not result in an economically significant concentration of rare metals; (ii) at  $986 \pm 10$  Ma; the so-called Kibaran “tin granites” were emplaced. After intrusion of “tin granites”, pegmatites were emplaced at  $968 \pm 8$  Ma (Rb-Sr isochrones)(Brinckmann et al., 2001).

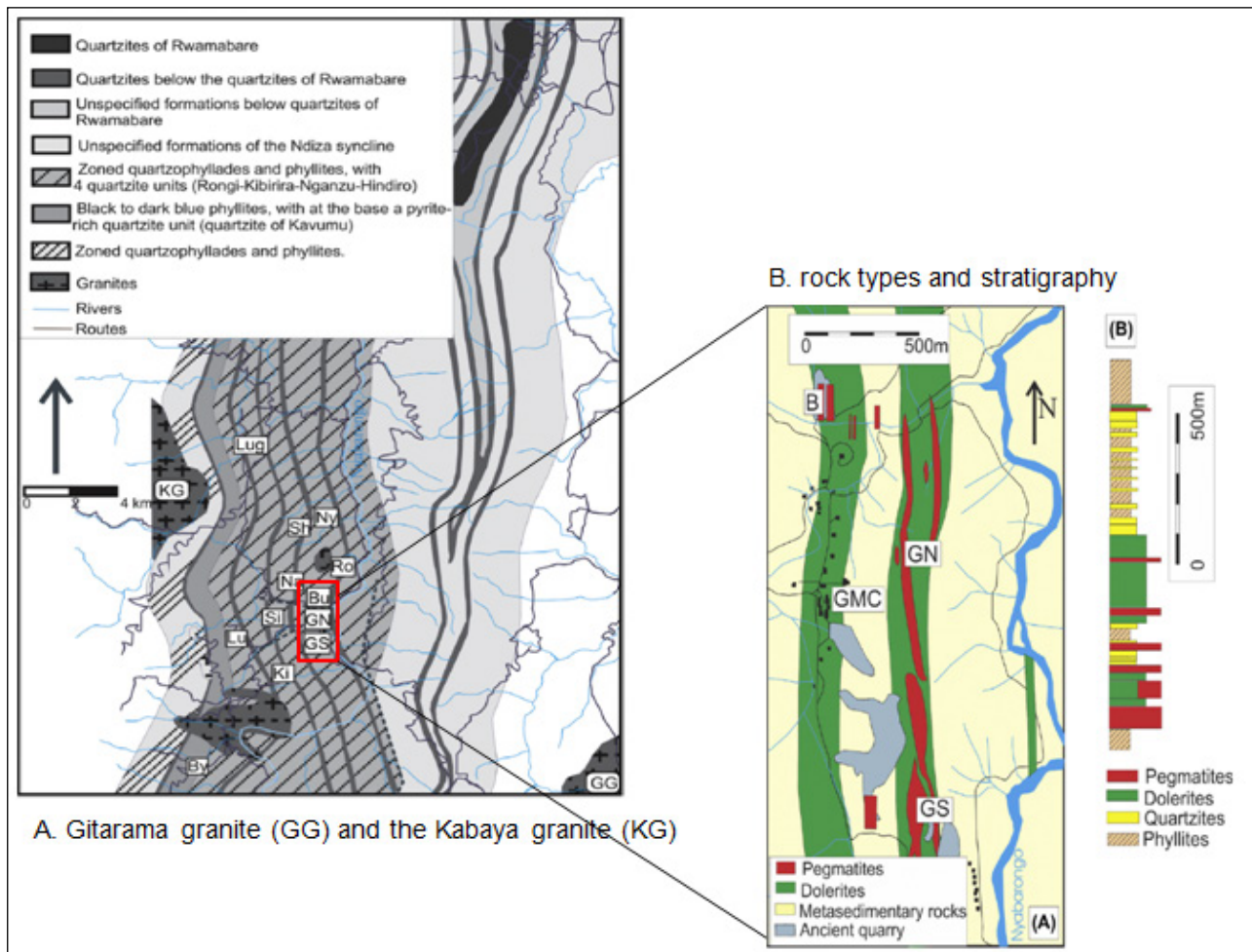


**Figure 5:** Location of Gatumba Mining District in the Western Province of Rwanda

Geologically, the Gatumba mining zone is located between two granitic terrains: the Gitarama Granite to the east and the Kabaya Granite to the west (Figure 6). The geology is dominated by schist formations. It comprises an alternation of Mesoproterozoic, metapelites and quartzites (Dewaele et al., 2011). The regional metamorphism of the Western Rwanda is described to be in general low-grade greenschist metamorphism (Baudet et al., 1988). However, the presence on a very local scale of minerals like biotite, andalusite and actinolite in Gatumba (Gérards, 1965) could indicate, according to (Dewaele et al., 2011) a higher metamorphic grade (Dewaele et al., 2011). This strong local variation in metamorphic assemblages in the Gatumba area has been interpreted to be caused by contact metamorphism through the granite intrusions (Gérards, 1965).



The metasedimentary rocks in the Gatumba area are intruded by mafic dolerites and pegmatites (Gérards, 1965; Dewaele et al., 2011). The numerous pegmatites characterizing the Gatumba area are variably mineralised in columbite-tantalite and/or cassiterite (Dewaele et al., 2011). More than 130 larger pegmatite bodies have been identified and mapped by companies in the area; MINETAÏN and SOMIRWA which are located between Lukaragata, Bijyojyo and the Nyabarongo River (Figure 6).



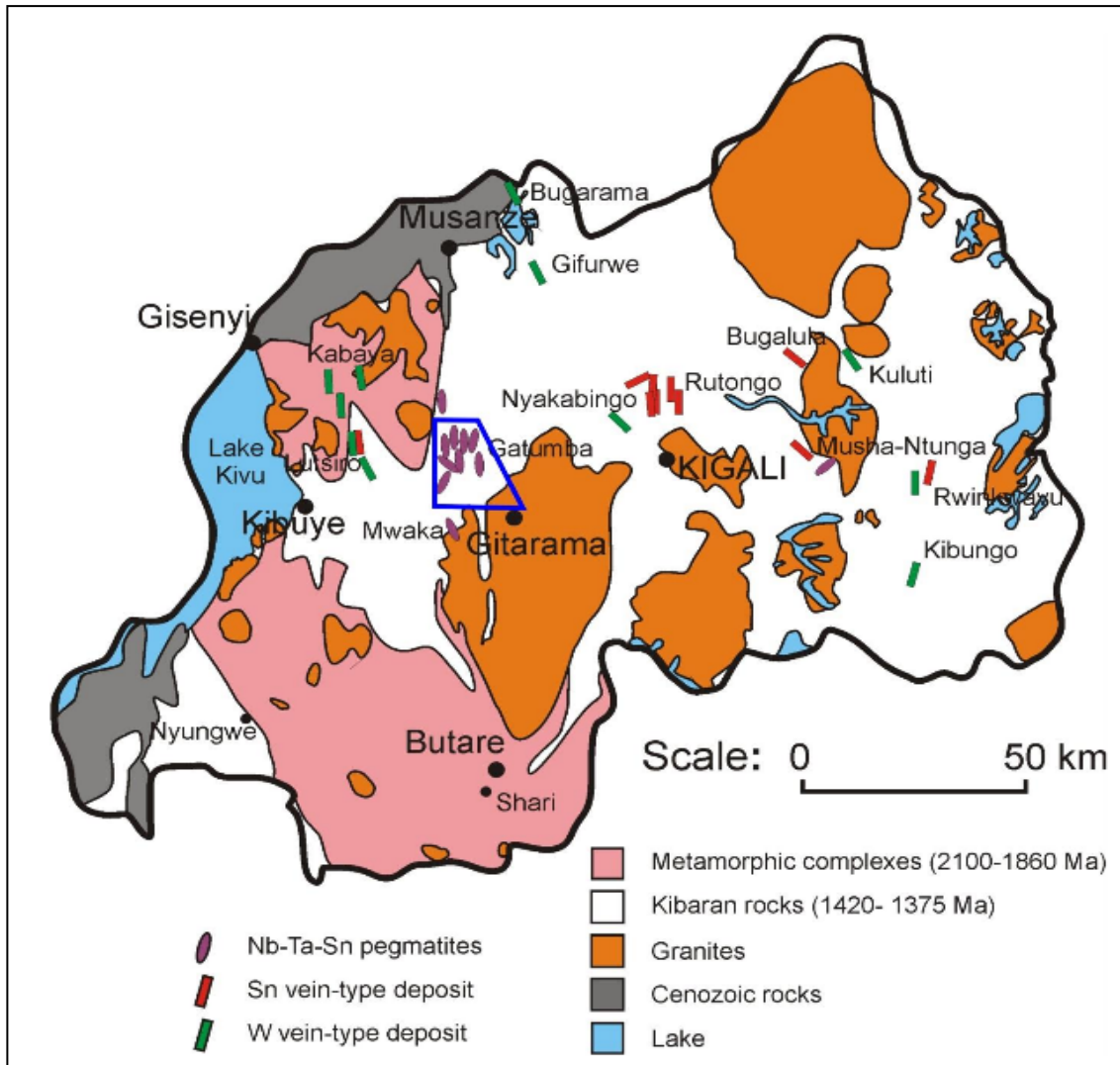
**Figure 6:** Geological map of the study area

**A.** Location of Gatumba Mining District between Gitarama granite (GG) and Kabaya granite (KG) **B.** main rock types of Gatumba and their stratigraphy. Bijyojyo (By), Buranga (Bu), Gatumba North (GN) and South (GS), Kirengo (Ki), Lugaragata (Lug), Luhanga (Lu), Nyarigamba (Na), Nyamissa (Ny) Rongi (Ro), Shori (Sh) and Sitwe (Si). The quartzites of Rwamabare are located in the centre of the Ndiza syncline (modified from Dewaele et al., 2011)

The mineralisation in Gatumba Mining District is representative for the pegmatite related mineralization in the Kibaran (Pohl et al., 2008). It presents numerous mineralized pegmatites, which are related to the Central African Tin-Tantalum province, and which are mined semi-industrially and artisanally (Dewaele et al., 2007). The pegmatites are dated at ~968 Ma, of which some are associated with columbite [(Fe, Mn)



(Nb-Ta)<sub>2</sub>O<sub>6</sub>], cassiterite (SnO<sub>2</sub>) and wolfram [(Fe,Mn)WO<sub>4</sub>], beryl, [(Be<sub>3</sub>, Al<sub>2</sub>Si<sub>6</sub>O<sub>18</sub>), spodumene [LiAlSi<sub>2</sub>O<sub>3</sub>], amblygonite [LiAlFPO<sub>4</sub>], monazite [(CeLa,Y,Th)PO<sub>4</sub>], gold (Au), bismuth (Bi) mineralization, etc. (Dewaele et al., 2007). They occur as primary mineralisation in quartz veins, greisens and pegmatites (Figure 7), but also as secondary mineralisation in alluvial or eluvial deposits. The presence of these minerals attracted the interest of mining industry, depending on the international demand.



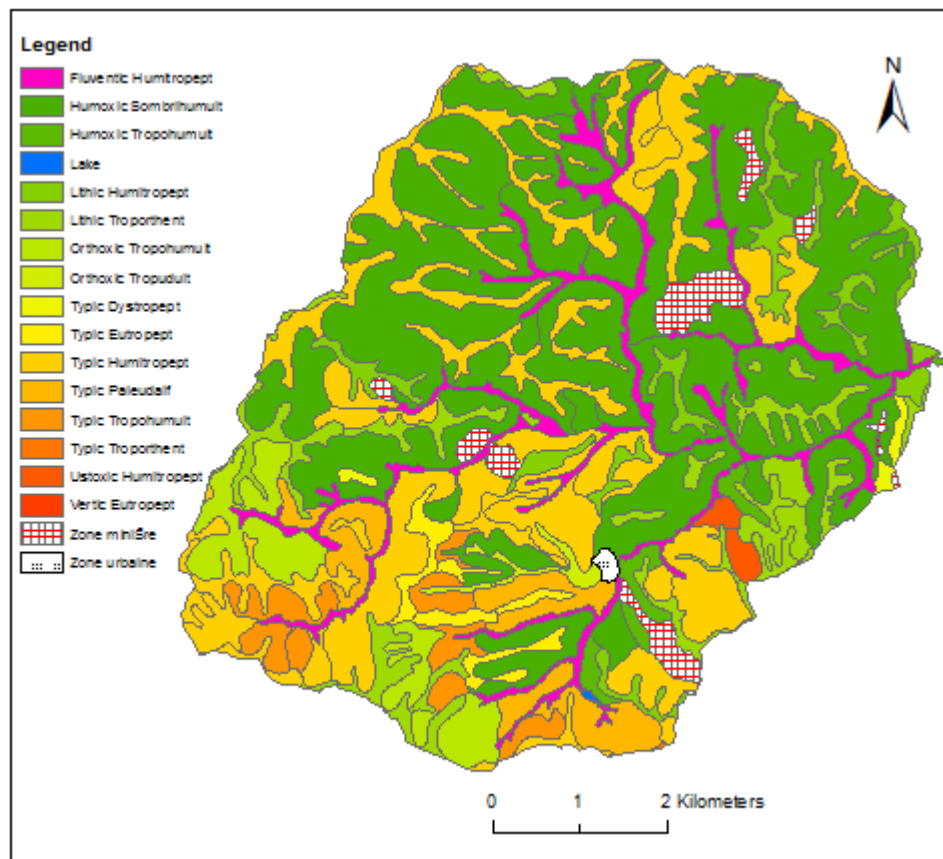
**Figure 7:** Simplified location map of the main deposits of tin, tantalum and wolfram in Rwanda (Muechez et al., 2014)

Among the listed minerals in previous paragraphs, coltan, a colloquial name for columbite (niobium oxide) [(Fe<sub>2</sub>, Mn) Nb<sub>2</sub>O<sub>6</sub>] and tantalite (tantalum oxide) [(Fe<sub>2</sub>, Mn)(Ta,Nb)<sub>2</sub>O<sub>6</sub>], and cassiterite (tin ore) (SnO<sub>2</sub>), are the most exploited in Ngororero District, and the largest deposits located in Gatumba sector, are mostly contained in pegmatite intrusions but also important quantities are found in vein-type deposits..

### 3.1.3 Soil and land use

The study area presents a clayey soil. This fine-textured soil develops on siliceous, schists and weathered mafic intrusions. The pedological map of Rwanda (Birasa et al., 1990) shows two dominant sub-groups of soils in the study area (Figure 8).

- The fluventic humitropept that occupies valley floor. These are alluvial mostly brown or coloured soils that formed in recent water-deposited sediments. Most of these alluvial sediments are derived from eroding soils and contains a relatively high amount of organic matter (OM) associated with clay fraction.
- Humoxic sombrihumult found mostly on foot-slope and/or back-slope positions. These soils are humus-rich Ultisols widely distributed in mountainous areas that have high rainfall but also have a moisture deficit during some season.

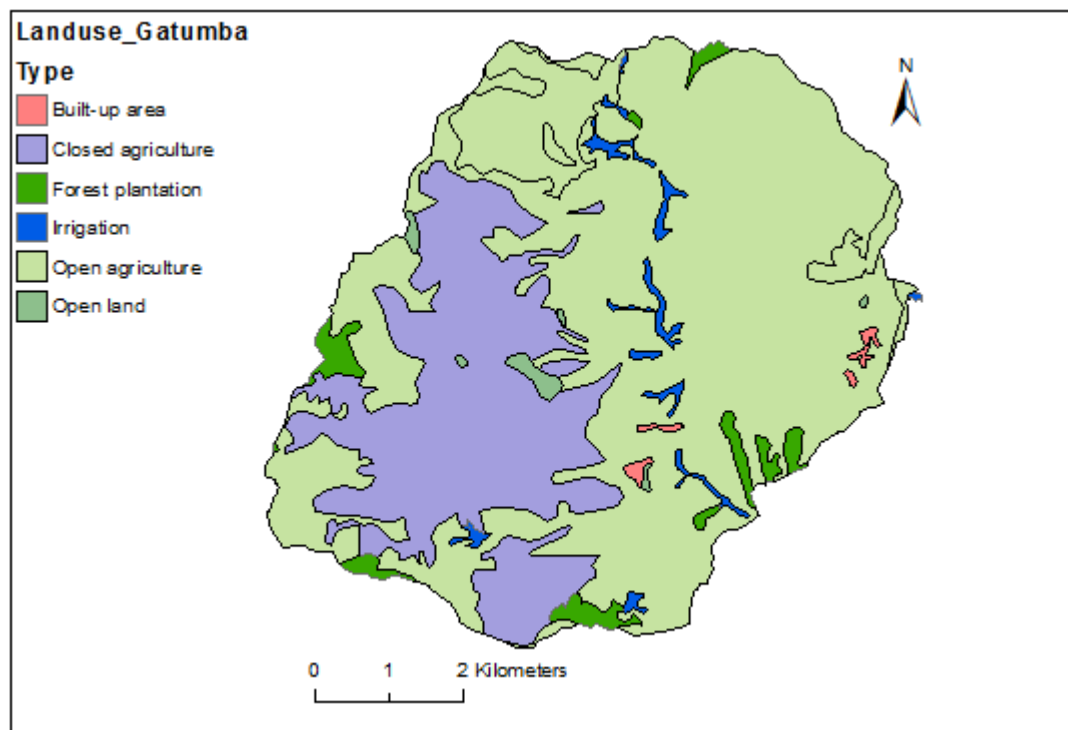


**Figure 8:** Taxonomy of soils of Gatumba Watershed

Sombrihumults is a great soil group within humults, with soil having a sombric horizon within 100 cm from the mineral soil surface. Fluventic humitropept is a sub-group within inceptisols with a diagnostic cambic horizon rich in organic matter. This soil type is formed on alluvial plain constituted of enriched

soils from upslope transported under the influence of erosion process. The soil occupies relatively small areas in comparison with humoxic sombrihumult.

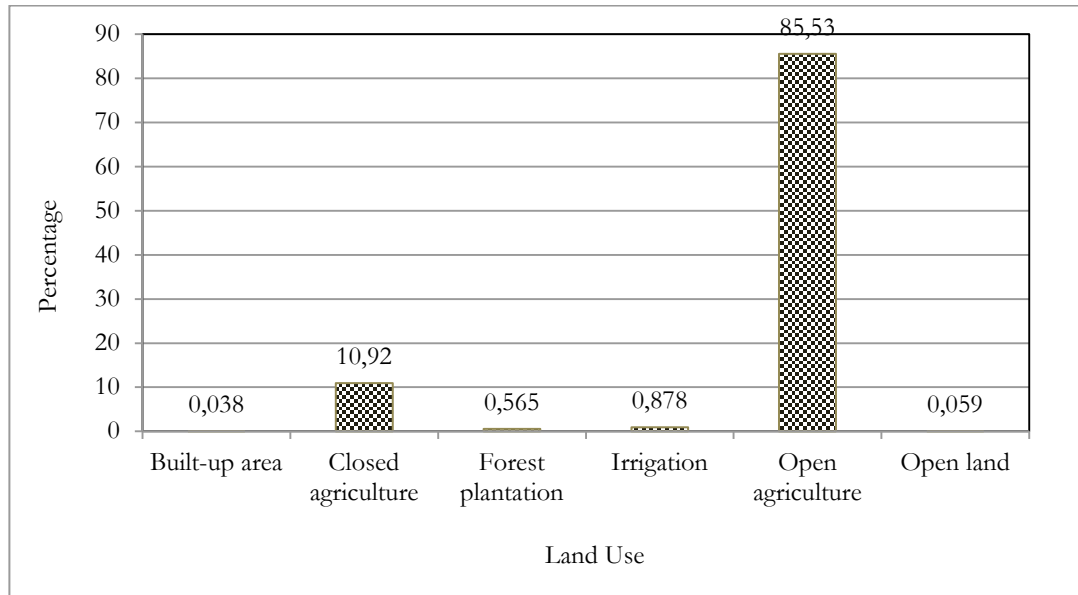
Land Use in the Gatumba Mining District (Figure 9) can be described in the context of rural areas of Rwanda. 90 per cent of the population are involved in subsistence farming practices, highly dependent on favourable growing seasons (Warnest et al., 2012). Agriculture contributes over 36.7% of the GDP (in 2010 year) (Warnest et al., 2012). However, agriculture including mining is the major form of land use in the Gatumba District that constitutes the backbone of livelihood and economy, with most farmers producing a wide variety of crops. Nearly all cultivating households produce at least one staple crop and the majority also produces a range of fruits and vegetables.



**Figure 9:** The land use map of the Gatumba Watershed

In the Gatumba watershed, the land cover predominantly agriculture was classified into 6 (Figure 10). The area is subject to nonstop exploitation which requires sustainable measures to control soil erosion on steep slopes characterizing the district. The agriculture system is predominantly “open” with 85 % of total land, while 11 % of the land is used for “closed” agriculture. Steep slopes characterizing the extensive part of the watershed with continuous farming (90%) are more vulnerable to accelerated soil erosion than flat slope areas which actually present approximately less than 10 %. Geomorphic processes in such areas

intensively exploited for agriculture and SSOM in high erosion risk zones could in principle be ascribed to both natural and human activities.

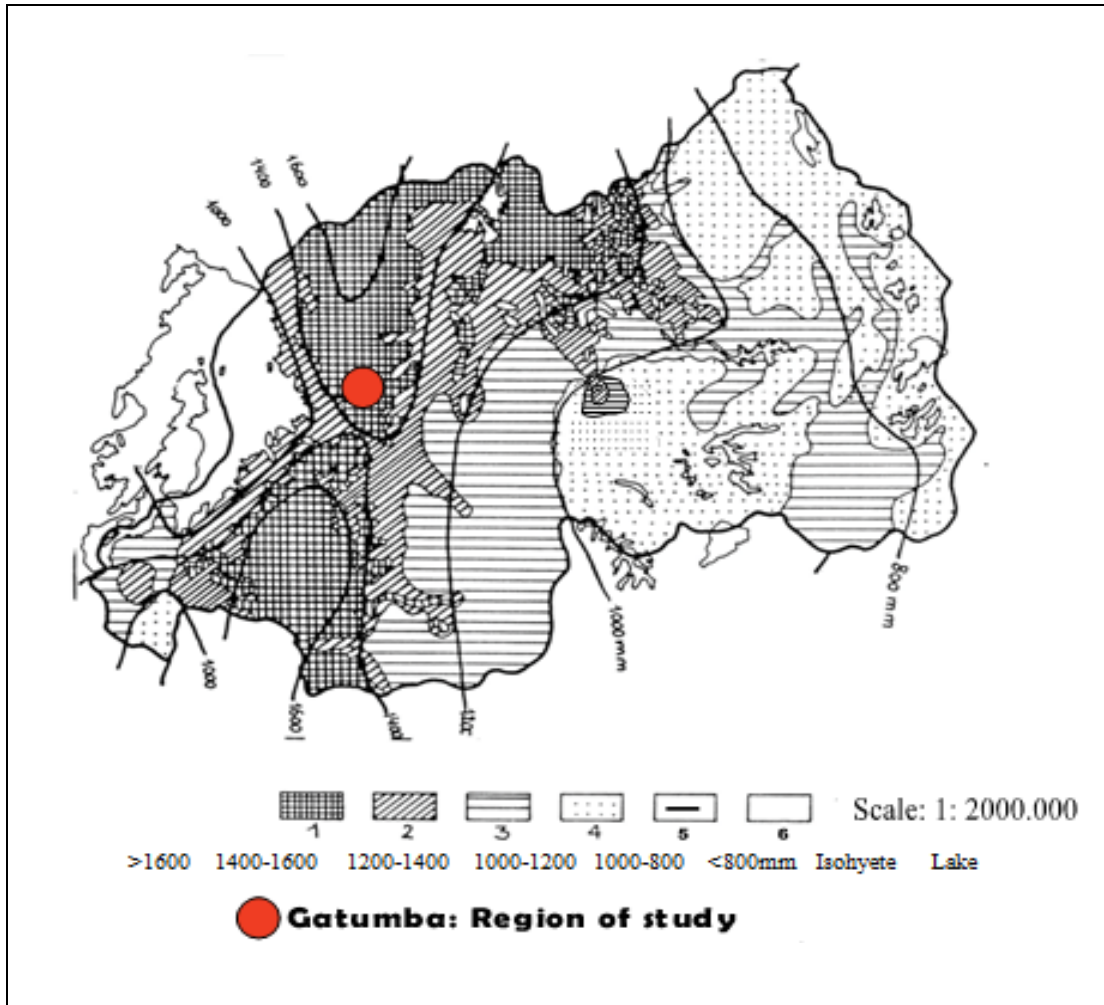


**Figure 10:** Total Area of Land Use in Gatumba Catchment

### 3.1.4 Geomorphology

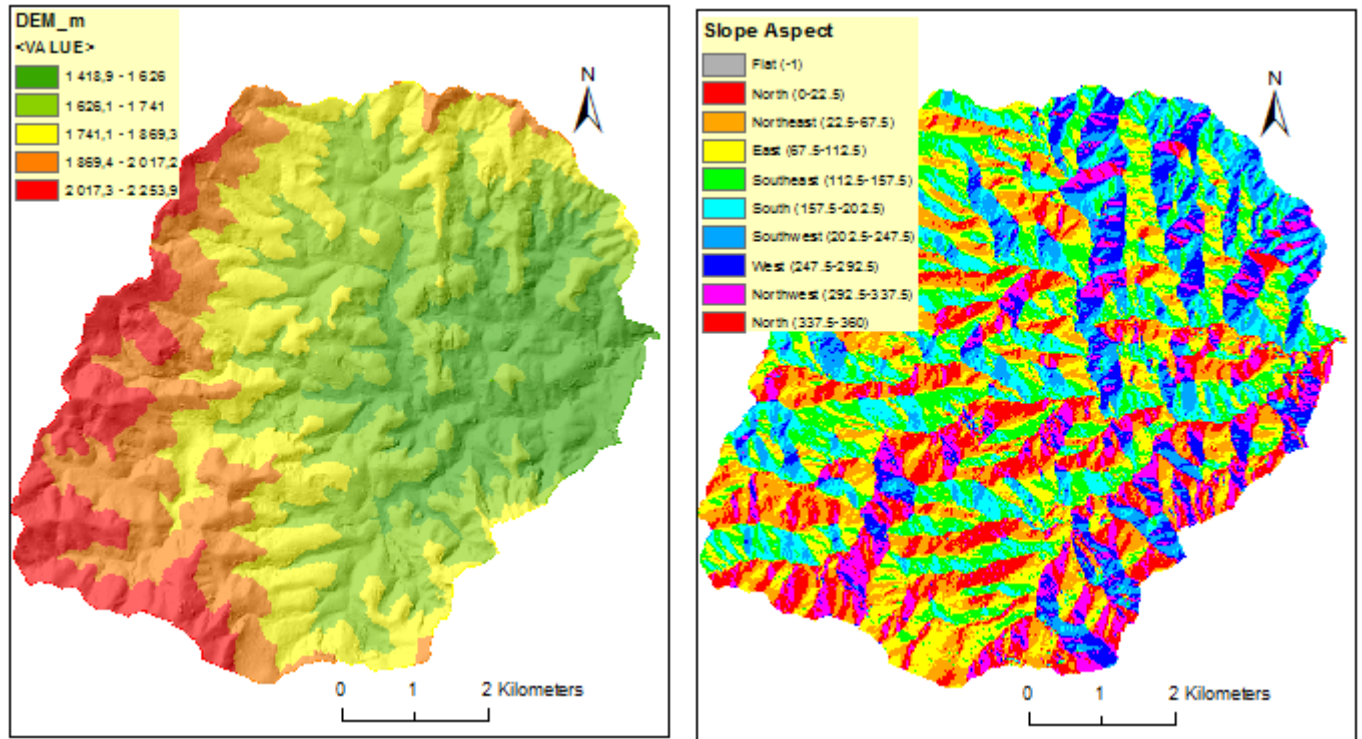
The relief of Rwanda is characterized by the existence of a series of planation surfaces. The landscape rises from the East (low plateau of Akagera) to the highest outliers in the West Congo-Nile Watershed Divide (CNWD)(Figure 11). The geomorphological location of the Gatumba region lies at the intersection of the Butare and the Byumba surface with the CNWD. The watershed is deeply dissected by rivers Kibilira and Kirombozi, and their tributaries, Gisuma and Kavugangoma, which drain their water eastwards to Nyabarongo, the main river in the region.

This dissection resulted in a landform characterized by steep hills by groove-shaped valleys. These valleys are drained by numerous small streams which become important during the rainy season. The valleys of the Gatumba area resemble the groove-shaped valley style in crystalline rocks described by Louis (Thomas, 1974); they have steep slopes and varying width of bottoms. The transverse profiles show that the valley shape in general is asymmetric. Slope associations are mainly convex-rectilinear-concave.



**Figure 11:** Geomorphic planation surfaces and correlated rainfall in Rwanda(modified from Barambirwa, 1992)

Figure 12 shows the elevation and slope aspects, and Table 5 summarises the analysed physical characteristics of the sub-catchments of Gatumba watershed. Figure 13 shows the positions of studied mines in relation to flow paths in the catchments. As mentioned in the paragraph above, Kibilira and Kirombozi rivers and their tributaries: Gisuma and Kavugangoma, flow in a dendritic stream pattern to Nyabarongo in a “centrifugal network” of flows (Bendjoudi, 2002). In general, the valley sides of the main tributaries of the Nyabarongo are predominantly facing north or south.

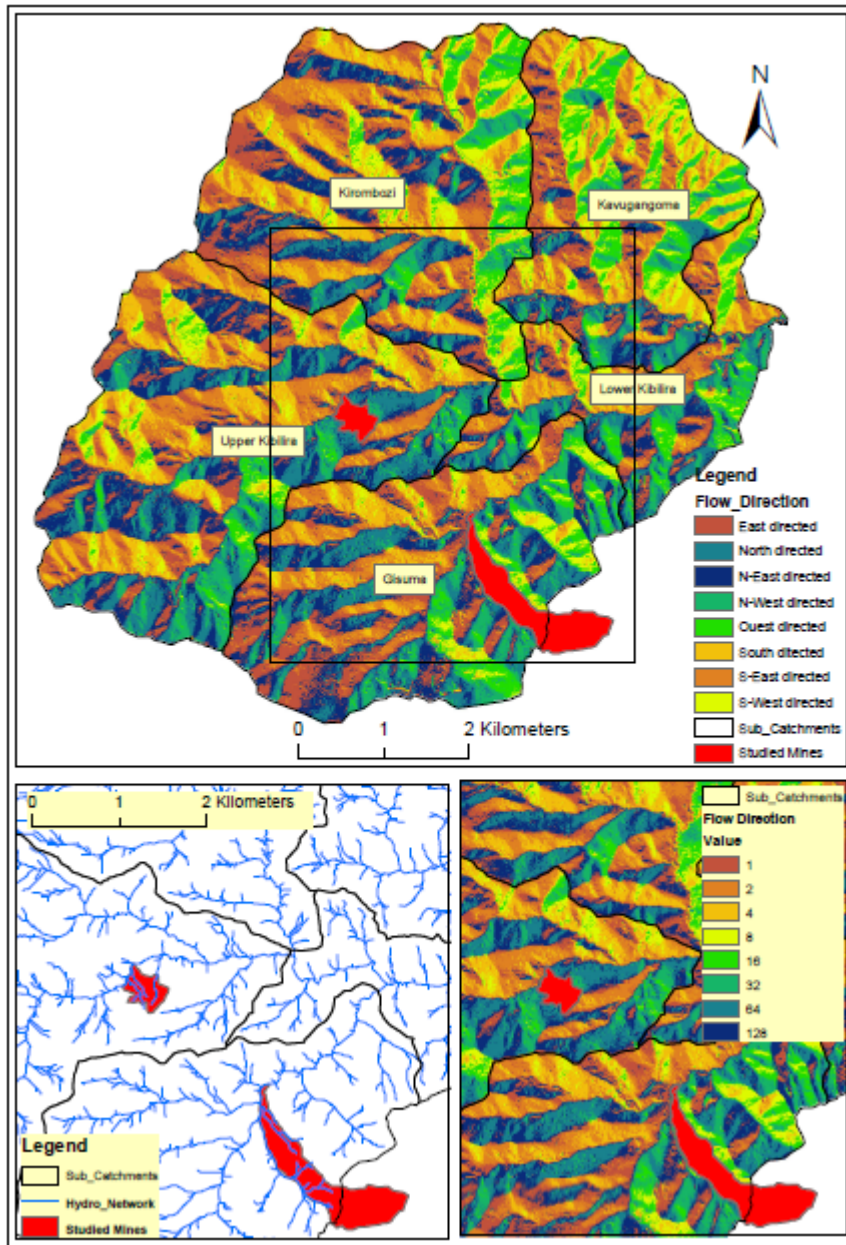


**Figure 12:** Elevation and Slope Aspects of the Studied Watershed of Gatumba Sector

**Table 6:** Physical properties of sub-catchments of Gatumba watershed

Sub-catchment	Gisuma	Upper Kibilira	Kirombozi	Kavugangoma	Lower Kibilira
Properties of the basin					
A (Area) [km <sup>2</sup> ]	10.14	13.6	11.81	8.27	5.55
L (Longest flow path) [km]	5.43	6.05	5.21	4.46	3.52
S (average slope) [%]	25.8	28.8	24.7	25.7	21.2
P (perimeters) [km]	15.38	17.9	17.2	13.6	11.8
a (Caquot lengthiness)	1.71	1.64	1.52	1.55	1.49
FF (Form Factor)	0.34	0.37	0.44	0.42	0.45
B <sub>s</sub> (Basin Shape Factor)	2.91	2.69	2.30	2.41	2.23
R <sub>E</sub> (Elongation Ratio)	0.66	0.69	0.74	0.73	0.75
R <sub>C</sub> (Circularity Ratio)	0.54	0.53	0.50	0.56	0.50
C <sub>c</sub> (Compactness Coefficient)	1.36	1.37	1.41	1.33	1.41
Rank	2	3	4	1	5





**Figure 13:** Position of studied mines compared to drainage flow direction system

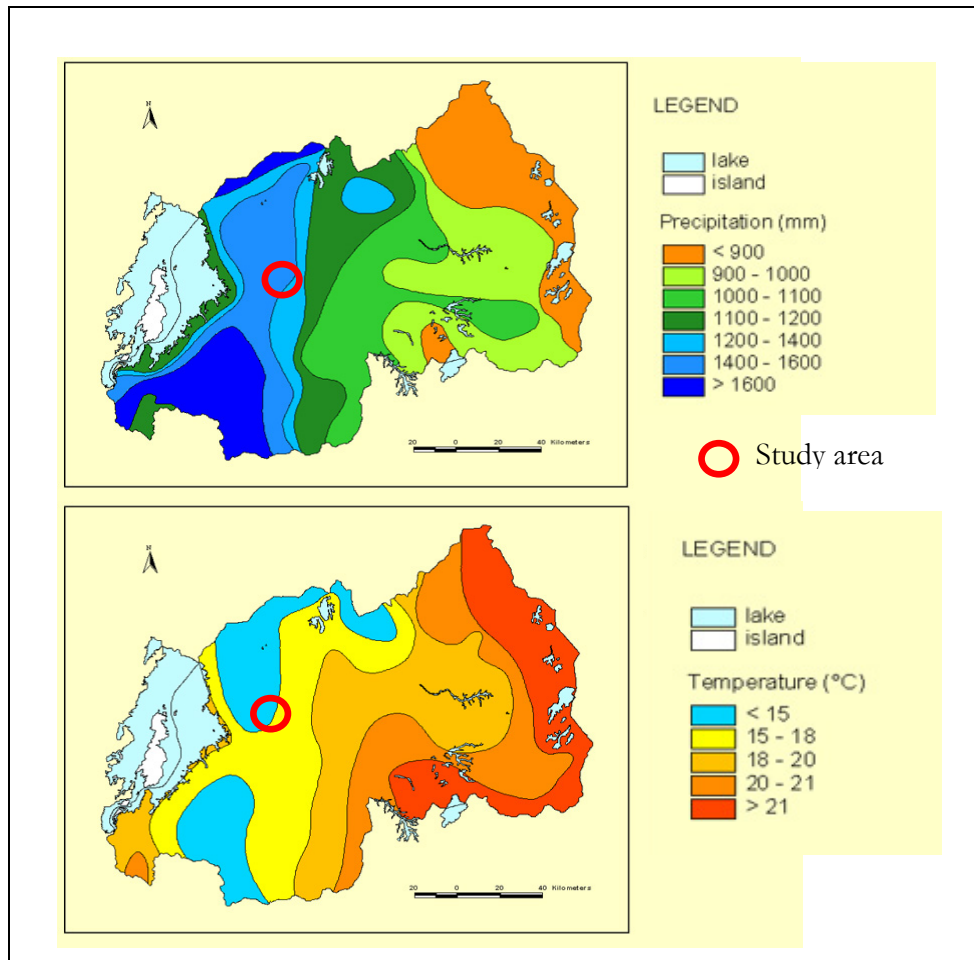
As shown on the map, flows (streams) pass through the mines. This position can be reasonably interpreted as favourable for increased sediment translocation and mass movement by relating the inflows to areas of working. Therefore, natural resources are likely to be affected by mining project development, such as process water and drinking water supplies as well as surface water bodies located downstream of project components (Kreps, 1997). In addition to translocation of soil components from the mine sites, chemical and mineralogical constituents are often dissolved and washed out.

The hydrological network of Gatumba is constituted of Kibilira River which crosses the entire watershed. The main tributaries of Kirombozi and Kavugangoma flow southwards and that of Gisuma north-

eastwards. Sub-catchments are of small size with area ranging from 5.55 km<sup>2</sup> (Lower Kibilira) and 8.27 km<sup>2</sup> (Kavugangoma) for the smallest sub-catchments; and 10.14 km<sup>2</sup> (Gisuma), 11.81 km<sup>2</sup> (Kirombozi) and 13.6 km<sup>2</sup> (Upper Kibilira) for the relatively larger sub-catchments. The longest flow path is detained by Upper Kibilira (12.05 km), Kirombozi (10.9 km) and Gisuma (9.43 km) respectively. The lengthiness of Caquot sub-catchments varies between 1.49 and 1.71 and the Gravelius Compactness between 1.32 and 1.40.

### 3.1.5 Climate and hydrological budget

Despite being located in the tropical belt, Rwanda experiences a temperate climate as a result of its high elevation (Figure 14). The Albertine branch of the Rift Valley runs along the western side of Rwanda and much of the border with the Democratic Republic of the Congo (DRC) is mountainous (and volcanic) with elevation over 2,000 m (McSweeney & Ntaganda , 2011).

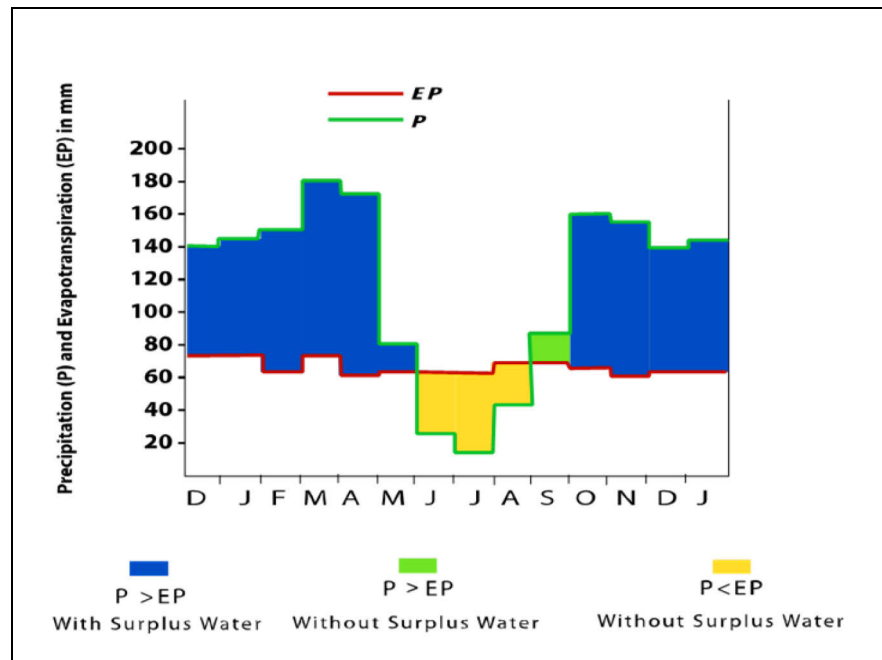


**Figure 14:** Annual means precipitation and temperature in Rwanda (modified from Verdoot and van Ranst, 2003)

Orographic lifting of predominantly south-eastern wind causes the precipitation to increase with altitude, while temperatures and evapotranspiration decrease. Rwanda is also characterized by a bimodal



precipitation regime. The majority of precipitation falls in two distinct seasons, (i) between mid-September and December followed by a short dry season during the months of January and February, and (ii) between March and May. The two rainy seasons are separated by a long dry season between June and August. In Gatumba, the average annual rainfall is 1370 mm with a mean monthly temperature of 20 °C.



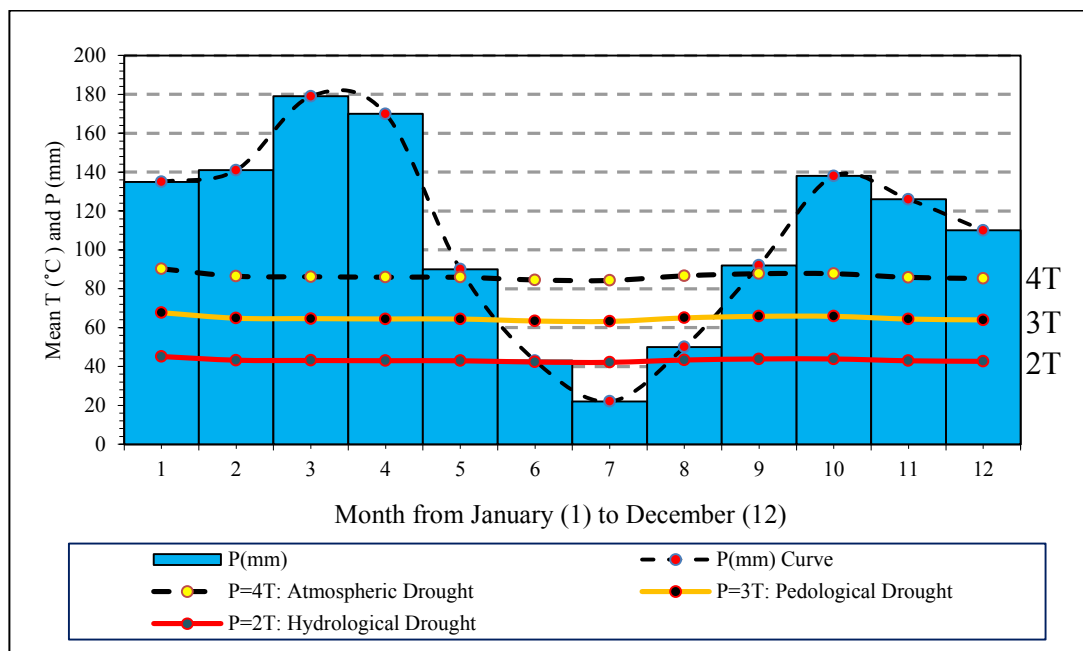
**Figure 15:** Hydrological budget in Gatumba area (Byizigi, 2008)

**Table 7:** Statistical results of hydrological budget in the Gatumba Mining District

Month	J	F	M	A	M	J	J	A	S	O	N	D	Year
t(°C)	22.6	21.6	21.5	21	21.5	21.13	21.1	21.7	21.9	21.9	21.5	21.3	
I	9.78	9.17	9.12	9.1	9.08	8.86	8.81	9.2	9.37	9.37	9.07	8.28	I: 109.89
Etp	3.1	2.9	2.8	2.8	2.8	2.7	2.7	2.9	3	3	2.8	2.8	
K	30.9	28.1	31.1	30	31.44	30.6	31.4	31.4	30.4	31.1	30.1	30.9	
ETP	96	81	87	85	88	83	85	91	91	93	84	86	
P	137	139	144	179	90	43	22	50	102	138	126	110	
P-ETP	16	50	57	94	16	-40	-63	-41	11	33	54	24	
∑deficiency	-	-	-	-	-	40	103	144	-	-	-	-	
RU	100	100	100	100	100	60	35	23	34	100	100	100	
Dru	0	0	0	0	0	40	25	12	-11	-66	0	0	
ETR	96	81	87	85	88	83	47	62	91	93	84	86	
ETP-ETR		0	0	0	0	0	38	29	0	0	0	0	
S	16	50	57	94	16	-	-	-	-	24	54	24	

T (temperature), i (monthly temperature index), I (annual temperature index), etp (potential evapotranspiration), k (rainfall coefficient), ETP (calculated potential evapotranspiration), P (precipitation), ∑deficiency (also called the Soil Water Deficit, is the gap between the amount of evapotranspiration water atmospheric conditions 'demand' and the amount soil can actually supply), RU (reserve use), Dru (difference of successive monthly reserves), ETR (real evapotranspiration), S (excess water that constitutes overflows).

The hydrological balance of the study area is summarized in the Figure 15 and Table 7. Average climate data over 30 years of closest rainfall stations have been used to estimate the hydrological balance and the potential distribution of rainfall, and the portion of rainfall which may participate in soil erosion. As it can be seen in Figure 65  $P > PE$  represents a situation where precipitation is higher than potential evapotranspiration and is more than 100 mm in a month leading to surplus for runoff;  $P > PE$  represents a situation without surplus water for runoff enough to replenish the soil water reserves;  $P < PE$  represents a situation of uptake of stored water by vegetation. The evolution of the hydrologic reserve use (R.U) remains big and saturated during eight months of the year (January to May, and October to December). Water surplus is observed during those eight months of the year. It constitutes, during these months, the overland flow or the runoff whose maximum occurs between March and April (land rain fall season), and between October and November. However, the March-April runoff is higher. From this hydrological balance it can be concluded that runoff observed during eight months of the year can cause high erosion in mining sites. The application of different drought indices enables to identify the tropical rainfall regime with a long rainy season which is actually associated with geomorphic processes such as soil erosion. In addition, these indices indicate season along the year which may have an impact on agriculture. Using climate indices two major seasons, wet (rainy) season over nine months, from September to May, and a dry season over three months, from June to August were identified. Using De Martonne, Gaussen, and Birot indices (Péguy, 1970), three types of drought were identified in Gatumba: atmospheric drought, pedological drought and hydrological drought (Figure 16).



**Figure 16:** Types of droughts in the study area

Atmospheric drought occurs whenever in the ombrothermic diagram the precipitation curve passes underneath that of  $4T$ . When  $P$  (precipitation) is lower than  $3T$  (temperature), the drought becomes stronger and causes the drought of soils, which lack sufficient moisture for plants. That is pedological drought. There is hydrological drought when  $P$  is lower than  $2T$ . There are not only atmospheric and pedological droughts but also underground reserves are negatively affected, rates of flow decrease and sometimes stream can dry out completely. The climate data of the study area shows the following characteristics:

- the atmospheric drought lasts three months and occurs from mid-May to mid-August
- the pedological drought lasts two months from June to August and
- the hydrological drought lasts one and a half month from June to July.

July is the month that is the most affected by drought, followed by August and June. The insufficiency in water reserve during this period necessitates a supply in water to maintain plant health during re-cultivation of mines. Generally, alternation of drought and wetness on an highly disturbed land might have an increasing effect in weakening soils which do not contain enough organic matter to stabilize them.

However, analysis of data shows months with rainfall excess that contributes to runoff, which occurs mainly around April and November. This was determined through the calculation of hydrological budget estimated from climate data (rainfall and temperature) averaged over 30 years, using Thornthwaite method (Péguy, 1970). The major components of the calculated water balances, as presented in Figure 6 consist of rainfall excess that constitutes runoff over a long period of the year which potentially has an important impact on geomorphic processes on hilly steep slopes and valleys that are locally mined.

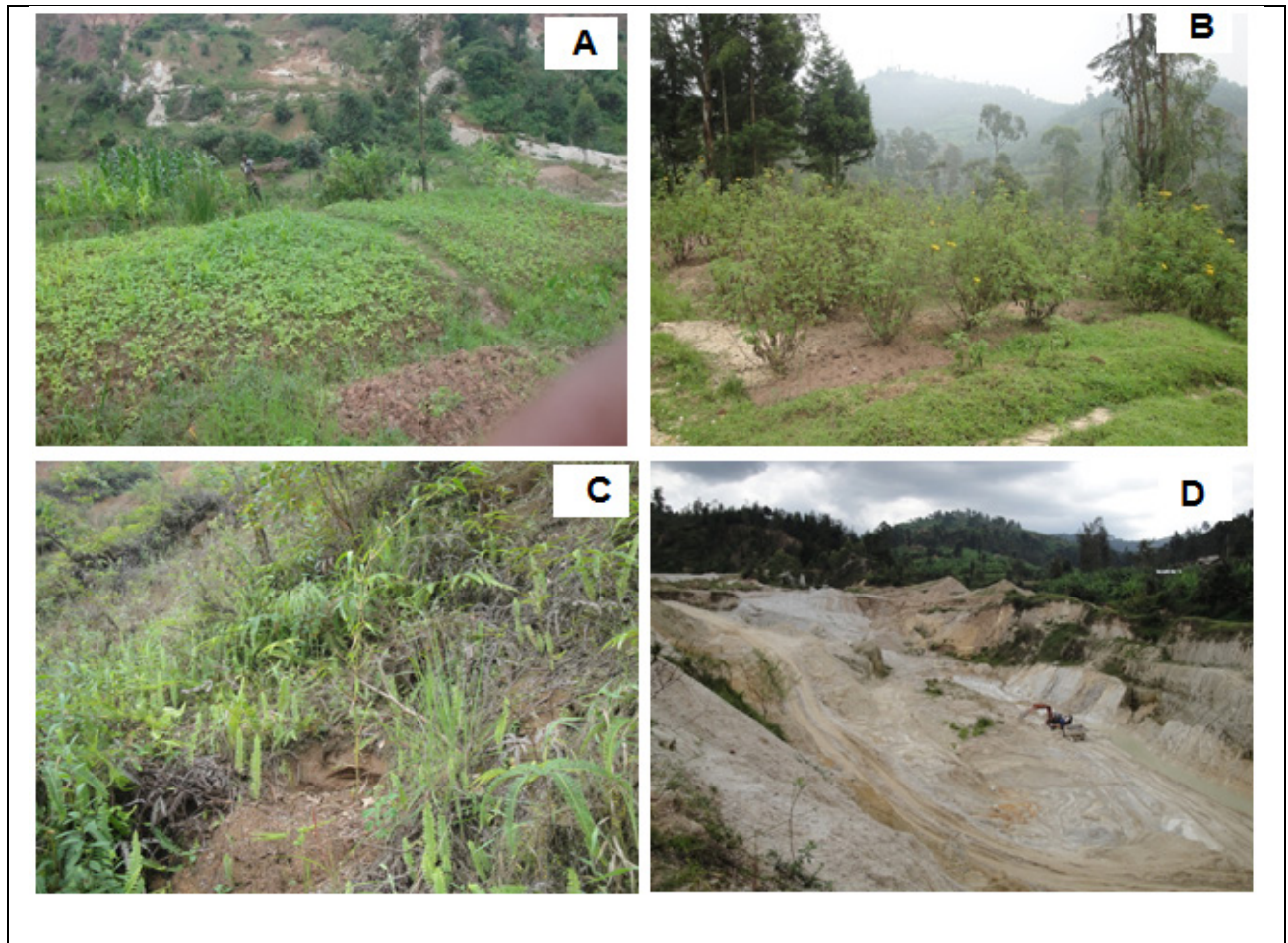
## **3.2 Field study and soil analysis methods**

### **3.2.1 Field study design and data collection**

In order to understand geomorphic processes in an area experiencing intensive land use such as mining among others, field survey, assessment of soil properties and erosion modelling, and the review of literature were required. Furthermore, additional data were obtained from diverse public services and projects reports on mining. These auxiliary data were useful as support documents mainly for mapping.

Field survey enabled to (i) identify geomorphic landforms directly or indirectly resulting from SSOM summarized in chapter 2 (Byizigiro et al., 2015), and (ii) locate suitable and representative mines with

regards to the objectives of the study. The criteria of such a selection was based primarily on different, fairly homogeneous land uses in selected mine sites which were classified in Ex-mine cultivated site (CS), Ex-mine reclamation site (ERS) and/or Ex-mine self-recovering site (SR), whose properties were compared with that of Control sites in the close proximity out of mining influence, which are not represented on the Figure 17 below. Mined sites (D) “lands being currently mined” have been identified but no sample was taken.



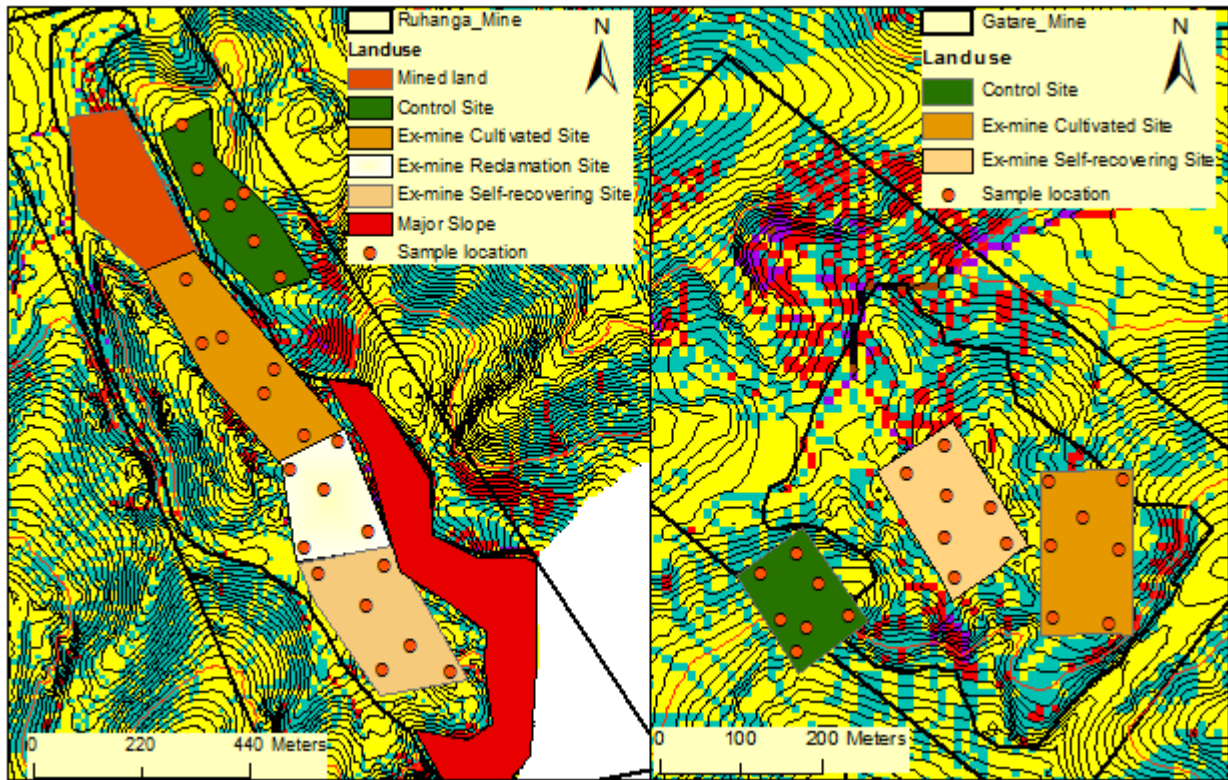
**Figure 17:** Categorization of mines into plots

A. Ex-mine cultivated site (CP); B. Ex-mine reclamation site (ERS) with *Tithonia Diversifolia*; C. Ex-mine Self-recovering site (SR); D. Mined site (Photographs taken between 2008 and 2014 by the Author)

Field experiments and laboratory analyses of soils were conducted to better understand alteration of affected sites. Laboratory analyses of properties of soils of direct relevance with geomorphic processes were performed. Most of data collected from the field were mapped with the help of GPS and integrated in GIS for mapping and modelling the soil erosion risks in the study area. 96 disturbed soil samples were drawn from 48 sites on both topsoil and subsoil layers, from different identified land uses of mines and control sites (Figure 18). These aimed at analysing soil texture, organic matter content and soil aggregation.



40 additional core samples were collected as well for assessing water holding capacity, soil bulk density and total porosity. Furthermore, seven core samples and seven disturbed samples were collected from the contact between A and Bt horizons, based on identified lithologies, to assess soil consistency, natural moisture content and dry bulk density.



**Figure 18:** Sketch of land use classes and sampling sites in Ruhanga and Gatare Mines

The major lithologies include schist, dolerite and pegmatite. Experiments for infiltration of water into the soil have been performed at sixteen locations within different land uses using double ring infiltrometer. Soil analysis was conducted at the University of Rwanda, in the Soil Physics Laboratory, School of Agriculture and Animal Husbandry, and the Geotechnics Laboratory, Civil Engineering Department, College of Science and Technology respectively. The literature enabled to get in the subject, to understand and interpret the concept of geomorphic processes of SSOM. Field study involved survey and onsite experiments. A GIS based modelling using RUSLE was applied for predicting soil erosion.

### 3.2.2 Analytical methods of selected soil properties

As the size of identified plots differs one from the other, the number of samples to be drawn by the proportion of the total plots contained within the study area have been weighted after Tan (2005). In this

study, analysed soil variables of prime relevance to assess geomorphic processes in Table 8 and analytical methods in Table 9 are briefly described in the following paragraphs.

**Table 8:** Relevance of measured soil properties in terms of geomorphic processes

Indicators of soil quality	Role or contribution to soil quality	Described by
Soil texture	Retention and transport of water, nutrients and gas, and overflow	(Doran & Parkin, 1994)
Organic Matter	Nutrient and water availability	(Tiessen & Moir, 1993)
Aggregate stability	Root growth, air water balance	(Arshad & Coen, 1994; Angers & Mehuys, 1993)
Soil bulk density	Root growth, rate of water movement, soil volume expansion	(Arshad & Coen, 1994; Larson & Pierce, 1994)
Soil porosity	Water balance, water retention	(Powers et al., 1998)
Infiltration	Water movement- storage and runoff	(Geeves et al., 2000)
Available water holding capacity	Plant available water, erosivity	(Arshad & Coen, 1994; Larson & Pierce, 1994)
Soil consistency limits	Cohesiveness of soils and slope stability	(Hazelton & Murphy, 2007)

### 3.2.2.1 Soil texture analysis

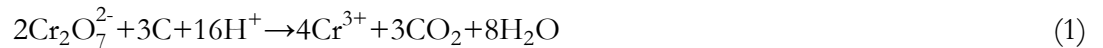
Soil texture analysis was performed using Bouyoucos hydrometer method (Gee & Or, 2002). Organic matter was removed with hydrogen peroxide ( $H_2O_2$ ), and a wet-sieving was performed through a 2 mm mesh. The soil fraction less than 2 mm was dispersed by shaking overnight with sodium hexametaphosphate reagent ( $NaPO_3$ )<sub>6</sub> ·  $Na_2O$ . Particle size was then analysed by the standard hydrometer method complying with settling time of soil particle in suspension. The USDA soil texture classification was used (clay < 0.002 mm, silt 0.002-0.05 mm and sand > 0.05 mm) (Tan, 2005).

**Table 9:** Analysed physical and chemical soil properties and methods

Parameters	Method
Soil texture	Hydrometer method (Gee & Or, 2002)
Org Matter Contents	UV spectrophotometer colorimetry after the standard wet chemistry technique (Tiessen & Moir, 1993)
Aggregate stability	Wet sieving method (Angers & Mehuys, 1993)
Dry Bulk Density and Porosity	Undisturbed soil core samples (Tan, 2005)
Soil moisture retention	Sand box, calculation of volumetric soil water content for pF 1/3 bar and pF 15 bar values (matrix potential) (Carter, 2002)
Infiltration	Double ring infiltrometer (Bertrand, 1965)
Atterberg' Limits	Plastic limits were determined following the method of fracturing threads of soils of 3 mm in diameter (Jumikis, 1983)
Natural Moisture Content	Undisturbed soil core samples (Tan, 2005)

### 3.2.2.2 Organic Matter Content

Organic carbon content (OC) was determined by UV spectrophotometer colorimetry after the standard wet chemistry technique. It was determined by the  $K_2Cr_2O_7$  (Potassium dichromate) wet combustion in  $H_2SO_4$  (sulfuric acid) medium. This method oxidizes carbon. The reduced chromium was dosed to 578 nm and corresponded to oxidized carbon according to the following reaction:



Organic matter was then calculated by Van Bemmelen's Correction Factor 1.724 (Péridé & Ouimet, 2007).

### 3.2.2.3 Bulk density and total porosity

The soil samples were measured with stainless Kopecky cylinders, and were oven dried at 105 °C till the constant weight is obtained. The soil bulk density (BD) was determined by dividing the mass of the dried soil by the volume of the cylinder. The total porosity (TP) was calculated from bulk density value following the equation 2. Porosity was then calculated directly from BD and the specific gravity (SG) of the soil particles called Soil Particle Density (SPD) usually assumed to be  $2.65 \text{ g cm}^{-3}$ , because the particle density of most soils is between  $2.6 \text{ g cm}^{-3}$  and  $2.7 \text{ g cm}^{-3}$  (Tan, 2005)

$$TP(\%) = \left(1 - \frac{BD}{SPD}\right) \times 100 \quad (2)$$

BD was selected as dependent variable to determine its statistical relationships with soil texture OM and TP: Factors affecting BD include TP, texture and OM. If they contain a well-balanced OM clayey soils tend to have a higher TP than sandy soils. However, the relationship between texture and BD is tenuous and depends on a variety of factors such as OM and depth of the soil profile.

### 3.2.2.4 Soil stable aggregates

Stability of soil aggregates was determined for topsoil (0-30 cm) and subsoil (30-60 cm) using a wet sieving apparatus (Figure 19). Stability measurement in this method depends on calculating the proportion of aggregates of a given size (1 to 2 mm) which do not break down into units smaller than a specific size ( $250 \mu\text{m}$ ) when immersed into water.

4 grams of 1-2 mm air-dried aggregates were put into each sieve and pre-moistened with distilled water. The sieves fixed in the sieve holder were placed in the cans filled with distilled water. The machine was run for three minutes moving up and down. Unstable aggregates passed through the sieve and settled in the cans underneath the sieves. Afterwards, the cans were removed and replaced by new cans filled with dispersing solution (Na-hexametaphosphate 0.2%). The machine was run again and sieving continued until

during 8 minutes, period required so that all stable aggregates have gone through the sieve and assembled in the cans. Only sand particles and root fragments were left on the sieve. Both groups of cans were completely dried in the oven at 105 °C for 24 hours. After that, the cans were weighed and the weight of aggregates in each can was calculated by subtracting the weight of can from the weight of can plus soil. A blank running only with the dispersing agent was subtracted from sample weight. The wet aggregate stability equalled stable aggregates weight divided by the sum of stable aggregates and unstable aggregates weights. The Wet-Aggregate-Stability method used in this work is more recommended if we need to measure soil stability at the scale of the whole soil or aggregate (>250 µm to 2 mm)(Hazelton & Murphy, 2007).

### 3.2.2.5 Water retention characteristics

Soil water retention characteristics (water holding capacity ‘WHC’ and permanent wilting point ‘PWP’) were determined using the sand box method supplemented by a pressure chamber. In the laboratory, the samples were placed in the sand box and saturated, and subsequently balanced at a specific moisture tension overnight. The variation in moisture tension was obtained by creating a series of pressures, at 1/3 bar for determining WHC, and at 15 bar PWP for determining respectively (Figure 19a-c). till all the water is extracted.



**Figure 19:** apparatus for determining soil aggregate stability and water holding capacity.

(a) Wet Sieve-Aggregate Apparatus (b) Sand Wetting Box (c) Manometer Pressure 5 bar max

Weighing the samples after each balance adjustment resulted in the volumetric water content for each moisture tension. Finally, samples dried up in the oven at 105 °C for 24 hours. After applying respective pressure to extraction a desired amount of moisture from the soil, WHC and the PWP were calculated as follows:

$$\text{WHC/PWP} = \frac{\text{Residual water in the soil}}{\text{Oven Dry weight of total soil}} \times 100 \quad (3)$$



The difference between WHC and PWP accounts for available water capacity ‘AWC’ for plants, whereas the difference between dried weight and fresh weight reflects the moisture content, or water retention, for each water tension. Plant available water holding capacity (PAWHC expressed in kL/ha) was obtained by applying equation 4 below:

$$\text{PAWHC} = \text{WHC} (\%) - \text{PWP} (\%) \times \text{thickness of measured soil layer} \times \text{BD} \quad (4)$$

### 3.2.2.6 Infiltration Measurement

Infiltration rates were determined at the sites using double ring infiltrometer (Bertrand, 1965). Two concentric cylinders, inner- and outer-ring of diameters 100 and 120 cm respectively, were driven into the ground up to a depth of 15 cm with a wooden mallet. A point gauge was fixed on the inner cylinder for measurement of the depth of water in it. The area between the two rings acts as a buffer zone and measurements only on the inner ring are used to calculate the infiltration rate. Infiltration characteristics of a soil was determined by ponding the water in the metal cylinder and then measuring the rate of water absorption of ponded water into the ground surface by registering the rate of fall of water level in the cylinder. The water depth is measured after frequent intervals until the rate of infiltration becomes constant.

Infiltration was performed on sixteen selected location, including control sites and Mines as well, where soil samples were collected in order to analyse the dependency of soil infiltration on selected soil properties, such as clay content, silt content and organic matter obtained using the laboratory test described above.

### 3.2.2.7 Atterberg Limits determination

Casagrande apparatus was used to determine soil consistency limits. These include (i) the Liquid Limits “LL” which is the water content corresponding to the arbitrary limit between the liquid and the plastic states of consistency of a soil, (ii) the Plastic Limits “PL” which reflects the limit between the plastic and the solid states of consistency of a soil, and (iii) the Plasticity Index “PI”, the difference between PL and LL which indicates the water content range over which the soil has plastic properties (Equation 5).

$$\text{PI} = \text{LL} - \text{PL} \quad (5)$$

PL and LL were determined following the method of fracturing threads of soils of 3 mm in diameter (Jumikis, 1983). Soil samples used for liquid limit determination were in their natural or moist state.

Dry bulk density of soils and particle size distribution within the coarse fraction of the soils were determined using STANDARD ASTM E-11 test. Sieves were employed in the determination of the

particle size distribution the Unified Soil Classification System (USCS) was used to get soil classes. Charts for Atterberg properties and size grading curves for soil samples were prepared.

Shrinkage Limits (SL) were determined following equation 6 below:

$$SL = \left( \frac{M_1 - M_2}{M_2} \right) (100) - \left( \frac{V_1 - V_2}{M_2} \right) (\rho_w) (100) \quad (6)$$

$M_1$  initial mass in saturated state,  $M_2$  final mass in dry state,  $V_1$  initial volume of soil in a saturated state,  $V_2$  final volume of soil in a dry state,  $\rho_w$  water density.

Natural Moisture content called soil moisture content (or water content) is the amount of water which can be removed when a soil sample is dried at the temperature of 105 °C. It was tested following ASTM D2216 Standard. Moisture content is usually expressed as a percentage of the dry mass following the formula given below:

$$W = \frac{m_w}{m_d} \times 100 \quad (7)$$

Where,  $W$  is the moisture content %,  $m_w$  water mass soil sample (g) which is determined by the difference in mass of the sample before and after oven drying at 105 °C,  $m_d$  dry soil mass (g).

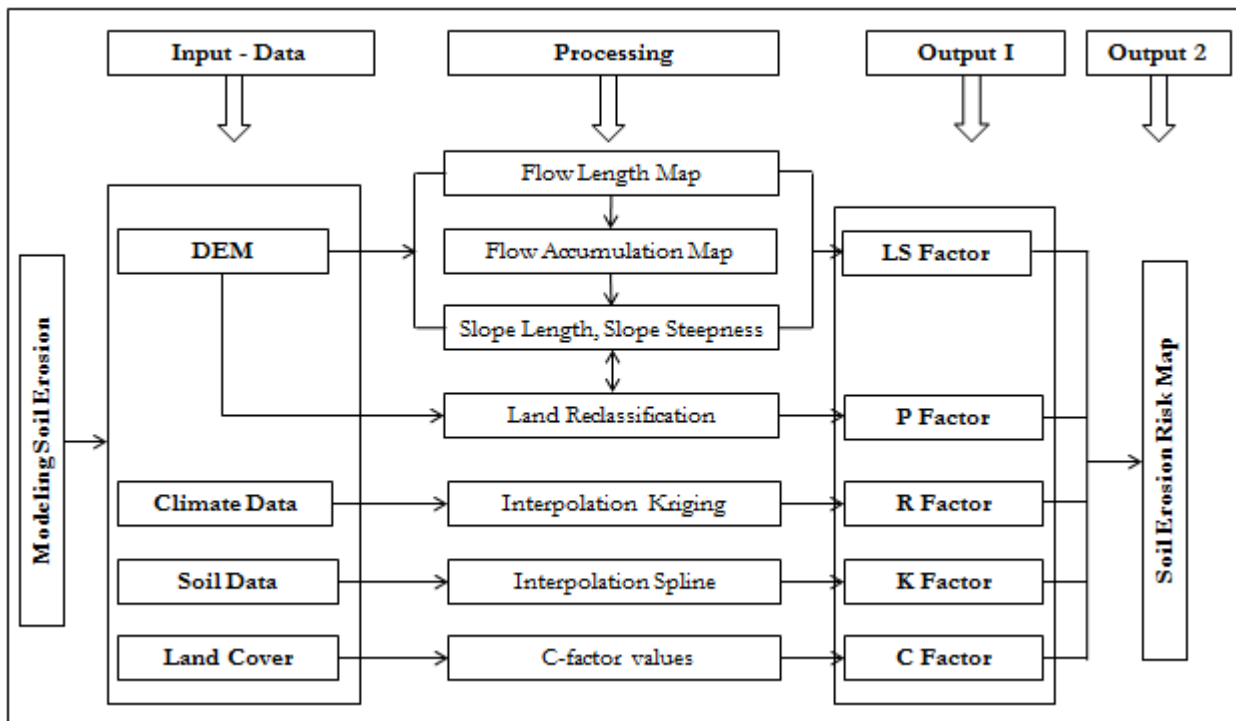
### 3.2.3 Soil erosion modelling

The Universal Soil Loss Equation (USLE) based modelling approach was selected as a tool to predict the average annual soil erosion risk in the reported project. USLE (Wischmeier & Smith, 1978), and its Revised Universal Soil Loss Equation (RUSLE) version (Renard et al., 1991) are the best renowned soil erosion modelling tools in the world (Drzewiecki et al., 2014). Although RUSLE was originally developed for application at the parcel scale, a topographic extension (Desmet & Govers, 1996) rendered the model appropriate for predicting annual soil erosion rates of small catchments with topographically complex landscape units. The overall methodology involved the use of RUSLE in a GIS environment. Individual GIS files were created for each factor and combined by cell-grid modelling to predict soil loss in a spatial domain.

The soil risk discussed here should not be confused with sediment yield. Sediment yield is the amount of eroded soil that is delivered to a point in the watershed that is remote from the origin of the detached soil particles. In a watershed, sediment yield includes the erosion from slopes, channels, and mass wasting, minus the sediment that is deposited after it is eroded but before it reaches the point of interest. RUSLE does not estimate sediment yield (Renard et al., 1997).

Despite some uncertainties regarding RUSLE, such as the overestimation of soil loss on plots with low erosion and underestimation of soil loss on plots with high erosion rate (Trabucchi et al., 2012), the model is yet suitable because it requires data that are relatively common and easy to be processed with GIS. RUSLE requires a set of dynamic data and support documents which are processed to get factors that enable to run the model, and which are computed to get the spatial average of total soil loss per year. The model accounts for annual soil loss value and soil erosion intensity in a given area. The RUSLE factors were calculated using equation 8. The flow chart (Figure 20) summarizes the major RUSLE processing steps and outputs. GIS is based on a combination of statistical analysis, database and cartography that allows the user to identify geographic information, relationships, patterns and trends of aspects being investigated (Onori et al., 2006). For this study, ArcGIS version 10 was utilized.

$$A = R \times K \times LS \times P \times C \quad (8)$$



**Figure 20:** Flowchart of soil erosion modelling

$A$  ( $t\ ha^{-1}\ yr^{-1}$ ) is the computed spatial average of total soil loss per year,  $R$  ( $MJ\ mm\ ha^{-1}\ hr^{-1}\ yr^{-1}$ ) is the rainfall erosivity,  $K$  ( $tha^{-1}$  per unit  $R$ ) is the soil erodibility factor,  $LS$  is the slope length and steepness factor (dimensionless),  $P$  is the erosion control - conservation practice factor (dimensionless),  $C$  is the land surface cover management factor (dimensionless).

Shapefiles, Digital Elevation Model (DEM), climate data, of the study area have been generously granted by various Departments of Rwanda Natural Resources Authority (Lands and Mapping, Integrated Water

Resources, Geology and Mines), the Rwanda Meteorology Agency, the Rwanda Agriculture Board, and the University of Rwanda-Centre for GIS and Remote Sensing. The DEM (10 m resolution) of the study area enabled to estimate slope length and steepness SL factor, cropping support P factor and other hydrological outputs such as flow direction, catchment area, flow length and flow accumulation. Additional secondary data used for this study, are shapefiles of the study area extracted from various maps of Rwanda: Pedological Map (1:50,000), Land Cover Map (1:50,000), Geological Map (1:50,000), Aerial Photographs of the region, (2.5m resolution), climate data, reports and reported research findings on the region. DEM 90 m resolution countrywide was used as a background map. Handheld Garmin GPSMAP 62sc colour screen (500\*450) was used for referencing samples and experimental sites.

### 3.2.3.1 Rainfall erosivity – R Factor

R factor represents the erosion potential caused by rainfall and runoff in a particular locality (Renard et al., 1991). This numerical value is used for the rainfall-runoff erosivity factor (R), both in USLE and in RUSLE to quantify the effect of raindrop impact and also to reflect the amount and rate of runoff likely to be associated with the rain (Renard et al., 1997). The RUSLE R factor for any given period is the average annual total of the storm  $EI_{30}$  values reordered on a given area.  $EI_{30}$  is the individual storm index values which equals to E, the total kinetic energy of a storm multiplied by  $I_{30}$ , the maximum rainfall intensity in 30 minutes (Morgan, 2005). The multiplication of EI reflects the total energy and peak intensity combined in each particular storm. To obtain an accurate R factor,  $EI_{30}$  needs to be calculated with continuous records over multiple years for multiple stations located at the area of the study site.

$$R = EI_{30} / 100 \quad (9)$$

Where

E is a kinetic energy of the rain ( $Jm^{-2}$ ) and I is the maximum rainfall intensity in 30 minute ( $mmh^{-1}$ ).

The average annual rainfall and runoff erosivity factor R ( $MJ mm ha^{-1} hr^{-1} yr^{-1}$ ) is the average of developed EI-values and is mathematically calculated as:

$$R = \frac{1}{n} \sum_{j=1}^n \left[ \sum_{k=1}^m (E)_K (I_{30})_K \right] \quad (10)$$

where E is the total storm kinetic energy ( $MJ ha^{-1}$ ),  $I_{30}$  is the maximum 30 min rainfall intensity ( $mm h^{-1}$ ),  $j$  is an index of the number of years used to produce the average,  $k$  is an index of the number of storms in each year,  $n$  is the number of years used to obtain the average R and  $m$  is the number of storms in each year (Renard & Freimund, 1994).

The above equation is however hardly applied in many regions including the study area because EI hydrograph data is available at standard meteorological stations. Therefore, many researchers use the modified Fournier index (MFI) (Morgan, 2005) sometimes written F. With this method, the rainfall aggressiveness is determined by considering the rainfall of all months following the equation 11 below:

$$\text{MFI} = \sum_{12} \frac{p^2}{P} \quad (11)$$

Where  $p$  is mean monthly precipitation and  $P$  mean annual rainfall.

Based on the above index, R-factor is calculated as follows:

$$R = 0.226 \text{ MFI}^{1.2876} \quad (12)$$

Researches on the applicability of monthly rainfall to estimate R-factor confirm the high correlation obtained with the MFI and R-factor. However, the formula above is the most used where monthly precipitations are available. When annual rainfall mean data alone are available, they can be interpolated to produce a map representing annual rainfall of a given region (Renschler et al., 1999). The produced map becomes the input source ( $P_a$ ) for the R factor calculation using the equation below for  $P_a > 850$  mm (Renard & Freimund, 1994):

$$R = 587,8 - 1,249P_a + 0,004105 P_a^2 \quad (13)$$

The used formula described by Bols (1978) in this work is suggested to be one of the most suitable equations to calculate R factor for humid regions. It is computed as follows:

$$R = 2.5 \times (P^2) / (100 \times (0.073 \times P + 0.073)) \quad (14)$$

$P$  is the average rainfall year ( $\text{mm yr}^{-1}$ )

Thus, meteorological data used in this study was recorded over 30 years (Appendix VII). The first step was to get R factor countrywide and the second one consisted of determining weighted moving averages (equation 26) to obtain R factor for the study area.

### 3.2.3.2 Soil erodibility - K Factor

Soil erodibility (K Factor) represents the susceptibility of soil particles to detachment and transportability of the sediment by rainfall and runoff as measured under standard conditions (Ashaq et al., 2011; Renard et al., 1997). It is the rate of soil loss per rainfall erosion index unit often determined using inherent soil properties (Pan & Wen, 2014). The standard condition is the unit plot, 72.6 ft long with a 9 percent gradient, maintained in continuous fallow, tilled up and down the hillslope (Renard et al., 1997). This

empirical measure of soil erodibility is affected by intrinsic soil properties (Fu et al., 2006), where soil texture and organic matter are the principal, but structure and permeability also contribute (Renard et al., 1991).

K in standard condition is normally determined using the following formula:

$$K = \frac{(10 \times 10^{-4}(12-OM)M^{1.14} + 4.5(S-3) + 3.0(p-2))}{1000} \quad (15)$$

Where: *K*: Soil Erodibility Factor (t ha<sup>-1</sup>)/ (ha hr<sup>-1</sup>/MJ mm), *M*: (% silt +% very fine sand) x (100 – % clay), *OM*: % of organic matter, *S*: Soil structure code, and *p*: Permeability code

Although *K* is commonly measured under field standards unit plots, alternative has been obtained to estimate soil erodibility from geologic formation found in the area (Karydas et al., 2009), or by considering soil attributes mostly particle size distribution and organic matter content proposed by (Schwab et al., 1981).

**Table 10:** K factor estimated from the geological formation found in the area (Karydas et al., 2009)

Parent material	Soil type	K-factor
Alluvial deposits	Sandy Loam, Loam	0.15
Limestone	Clay, Silty Clay	0.4
Peridotite	Clay Loam, Clay	0.5
Granite	Sand, Sandy Loam	0.2
Schist	Loam	0.7
Gneiss	Sand, Loamy Sand, Loam	0.3
Tertiary deposits	Sandy Loam, Loam	0.15

Many other researchers used soil texture and organic matter summarized in (Table 11) below for estimating K factor (Ashaq et al., 2011; Schwab et al., 1981; Stone & Hilborn, 2012).

**Table 11:** K factor depending on soil texture and organic matter content (modified from Schwab, 1981; Stone and Hilborn, 2012)

Textural Class	Organic matter content		
	0.5 (%)	2 (%)	More than 2 %
Fine sand	0.16	0.14	0.06
Very fine sand	0.42	0.36	0.37
Loamy Sand	0.12	0.10	0.04
Loamy very fine sand	0.44	0.38	0.25
Sandy loam	0.27	0.24	0.12
Very fine sandy loam	0.47	0.41	0.33
Silt loam	0.48	0.42	0.37
Clay loam	0.28	0.25	0.28
Silt clay Loam	0.37	0.32	0.30
Silt Clay	0.25	0.23	0.26

Information is not available, however, for every soil about structure and permeability. The percentage of clay, silt sand and organic matter are therefore used for calculating K factor following the Harmonized World Soil Data Base (HWSD), according to the Proposed Alternative Soil Erodibility Factor (ERFACT) (Forkuo et al., 2013).

$$\text{ERFACT} = 0,32 * \left( \frac{\% \text{ Silt}}{\% \text{ Sand} + \% \text{ Clay}} \right) \quad 16$$

Both tables were used to assign K indexes to individual soil types based on the soil map of Rwanda. Equation 19 was used to calculate K values based on soil laboratory results for mine sites.

### 3.2.3.3 Slope length and gradient - LS Factor and hydrological analyses

The topographic factor (LS) reflects the influence of slope length and gradient on soil erosion. It combines the effects of LS a slope length factor (L) and a slope steepness factor (S). The slope length defined as the distance from the point of origin of overland flow to the point where the slope decreases enough that deposition begins, or the point where runoff becomes concentrated in a defined channel (Wischmeier & Smith, 1978). The steeper is the slope, the greater is the energy of runoff and the greater is the capacity of water to erode and transport sediment (Yang et al., 2013).

Various approaches and algorithms for quantifying the LS factor have been developed. Moore and Wilson's equation for calculating LS factor over three dimensional terrains (Yang et al., 2013) is the most simplified and useful because it takes into consideration the unit contributing area (UCA). UCA is defined as the area that drains to a specific point (Yang et al., 2013) and is obtained by multiplying flow accumulation grid with the cell size. For this study, the following equation largely described by (Yang et al.,

2013) was used to calculate a combined LS factor, because it takes into account the contributing area and slope steepness:

$$LS = \left( \frac{A_s}{22.1} \right)^m \left( \frac{\sin(\theta)}{0.0896} \right)^n \quad (17)$$

Where

$A_s$  = Unit contributing area (m),  $\theta$  = slope in radians, m (0.4-0.56) and n (1.2-1.3) are exponents

Although many equations exist to calculate the LS factor, most authors refer to that suggested by Wischmeier (1975):

$$LS = \left( \frac{\lambda}{\phi} \right)^m (0.065 + 0.045s + 0.0065s^2) \quad (18)$$

Where:

$\lambda$ : Sheet flow path length (m),  $\Psi$ : Constant (22.13), s: Average slope gradient (%), m: refers to Table 10

In Arc GIS, slope length and gradient are computed in single index which expresses the ratio of soil loss as defined by Wischmeier and Smith (Morgan, 2005) in the equation below:

$$LS = \left( \frac{X}{22.1} \right)^m (0.065 + 0.045s + 0.0065s^2) \quad (19)$$

Where:

X: slope length (m), s: slope gradient (%), X = (Flowaccumulation \* cellvalue),

X and SL as well as hydrological data required for modelling were all extracted from a DEM after performing fill and flow direction process. The extracted raster DEM under GCS\_2005 spatial reference coordinates was generated in ArcGIS 10 by using the inherent protocols.

$$LS = \left( \text{Flow Accumulation} \times \text{cell} \frac{\text{value}}{22.1} \right)^m (0.065 + 0.045s + 0.0065s^2) \quad (20)$$

### 3.2.3.4 Conservation practice –P Factor

The Support Practice factor (P) represents the impact of conservation practices on the soil erosion rates. By definition, P factor is the ratio of soil loss with a specific support practice corresponding to cultivation method (Renard et al., 1991). Contouring, strip cropping and terracing are the cultivation methods that strive to control soil erosion. P factor values range from 0 (very good man-made soil erosion resistance) to 1 (no-manmade resistance erosion facility) (Ashaq et al., 2011). As the support practices applied in the watershed cannot be reflected from a land use map, individual coefficients were assigned to slope intervals depending on the type of cropping suggested in (Shin, 1999).



**Table 12:** Support Practice Factor P (modified from Shin, 1999; Wilfredo, 1988)

Slope %	Contouring	Strip Cropping	Terracing	
			<u>Bench</u>	<u>Broad-based</u>
0-7.0	0.55	0.27	0.10	0.12
7.0-11.3	0.60	0.30	0.10	0.12
11.3-17.6	0.80	0.40	0.10	0.16
17.6-26.8	0.90	0.45	0.12	0.18
26.8>	1.00	0.50	0.14	0.20

In this study averaged values have been used and have been compared with that of other cropping systems suggested in Table12. Although on some hill slopes there are no support practices, important portion of the area presents mixed support practices, mostly terraces and contours.

### 3.2.3.5 Cropping management –C Factor

From the standpoint of soil conservation planning, the land cover (C Factor) is an essential factor, because land use changes that characterize, reduce or increase soil erosion are represented by this factor (Trabucchi et al., 2012; Khana et al., 2007). C factor is a ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow. It measures the effect of canopy and ground cover on the hydraulics of raindrop impact and runoff (Morgan, 2005), more specifically the effect of vegetation and management on the soil erosion rates (Renard et al., 1991).The C factor was determined from land cover map. Values for identified land uses were assigned to the corresponding C factor ranges from approximately 0 to 1. Lower the value is, stronger is the cover effect resulting in no erosion; higher the value, higher is the rate of soil erosion because there is no cover effect. Before they were used for modelling purposes all spatial datasets were converted from vector to raster form with a cell size of 10 m. To appreciate soil losses, we referred to scientific classification and description suggested for regions with more or less similar natural and agriculture characteristics to Gatumba area (Drzewiecki et al., 2014).

### 3.2.4 Statistical analysis of data

The dispersion of studied soil parameters towards the mean of data set ‘standard deviation’ ‘ $\sigma$ ’ was determined and the correlation coefficient ‘ $r$ ’ and regression coefficients were used to know the strength and the direction of relationship between soil parameters (equations 21 and 22).

$$s = \frac{\sum_{i=1}^n (x_i - \bar{x})}{n-1} \quad \sigma = \frac{\sum_{i=1}^N (x_i - \bar{x})}{N} \quad (21)$$

$$r = \frac{n \sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2} \sqrt{n(\sum y^2) - (\sum y)^2}} \quad (22)$$

Skewness and Kurtosis were also used. The Skewness ( $Sk$ ) measures the extent to which the bulk of data values in a distribution cluster to one side or the other of the mean (Wong & Lee, 2005; Katabuhi et al., 2012), and is calculated by the formula 23. The distribution is positively skewed when most variables are less than the mean; alternatively, a negatively skewed distribution has the bulk of the values greater than the mean.

$$Sk = \frac{\sum_{i=1}^n (x_i - \bar{x})^3}{n \sigma^3} \quad (23)$$

Kurtosis reflects the extent to which values in a distribution are concentrated in one part of the frequency distribution (Wong & Lee, 2005). A very sharp distribution represents a bulk highly concentrated over a range of values, whereas a flat distribution is one without a significant concentration of values within a narrow range of the distribution. Kurtosis,  $K$ , is computed as follows:

$$K = \frac{\sum_{i=1}^n (x_i - \bar{x})^4}{n \sigma^4} - 3 \quad (24)$$

A typical multiple, two-variable or simple linear regression model (Cook & Weisberg, 1999) was used as shown in equation 25, to determinate the influence of selected independent variables on soil dependent ones:

$$Y = k_0 + k_1 x_1 + k_2 x_2 + \dots + k_n x_n \quad (25)$$

Where

$Y$  = Dependent variable, for example soil bulk density

$x_1 \dots x_n$  = independent variables, for example silt content, clay content and organic matter of soil (%)  
and  $k_0, k_1, \dots k_n$  = Regression

Also in order to get figures of infiltration rate which can be statistically analysed, averaged moving method has been used to estimate infiltration rate for other soil locations. This very important technique is used to obtain missing values of spatial series data, and thereby to get an overall idea of the trend data set.

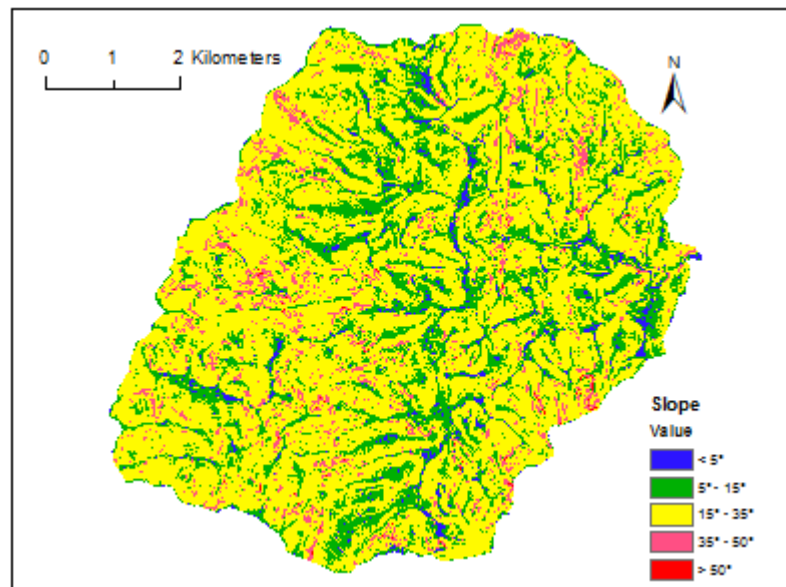
This was performed by using the following formula:

$$F_t = \frac{(2 \times A_{t-1}) + (1 \times A_{t-2} + A_{t-3})}{6} \quad (26)$$

## 4 Results

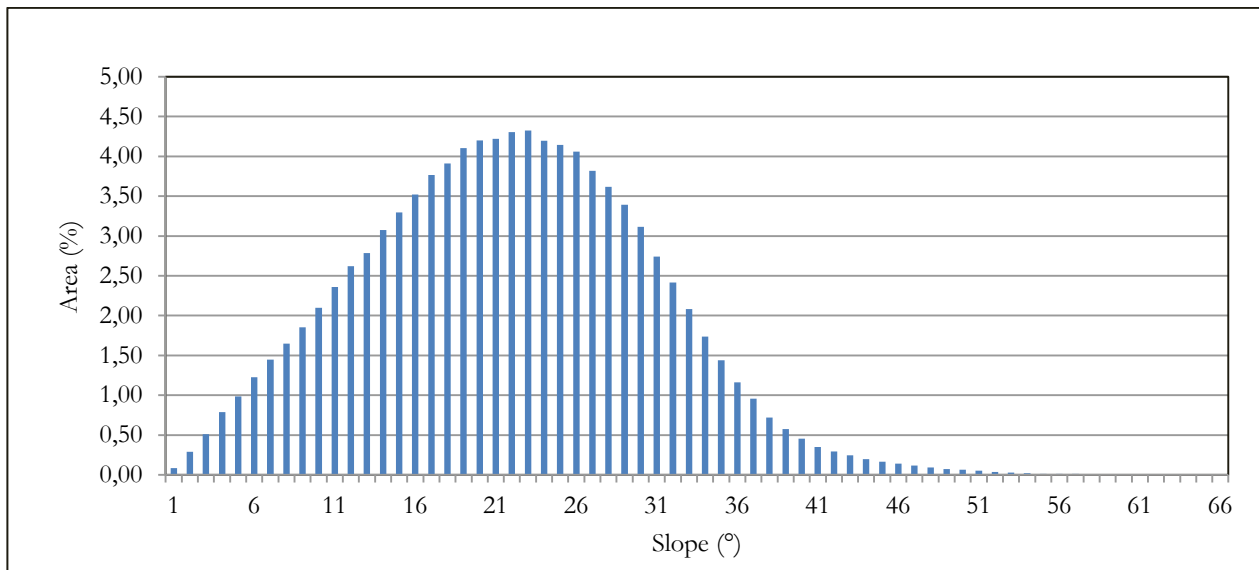
### 4.1 Morphometry description of the Gatumba watershed

The Gatumba watershed is dissected by numerous streams, and hillsides are generally characterized by steep slopes. Incised valleys vary from place to place. A local average in the area is calculated to 25 degrees with a maximum of 60 degrees (Figure 21). The transverse profiles show that valley form in general is asymmetric. Slopes association is mainly convex-rectilinear-concave. Locally unweathered Precambrian basement rocks are exposed in valley floors, where fluvial erosion has removed the regolith. This has probably resulted from the formation of great western rift valley in connection with the formation of the Congo-Nile Watershed Divide (CNWD) where Gatumba is located. Orderly, slopes of classes 15-35 ° and 5-15° dominate with 67% and 26 % respectively, followed by classes 55-50° and 0-5° with 4.5 % and 2.9 % of the total area; slope beyond 50° cover 0.1% only.



**Figure 21:** Distribution of slope in the study area

Steep slopes described for Gatumba are common for areas impacted by tectonic activity, where erosion would be expected to increase with increasing slope steepness and length. Westerberg(1999) noticed the similar geodynamics in Nyandarua mountain range located at the east African rift valley. Valleys have steep slopes and varying width of bottoms. Slope steepness and length are known to increase velocity and volume of surface runoff (Morgan, 2005). Furthermore, while on flat surface raindrops splash soil particles randomly in all directions, on sloping ground more soil is splashed downslope than upslope, the proportion increasing as the slope steepens (Morgan, 2005).



**Figure 22:** Area distribution in relation to slope

The geomorphology of Gatumba watershed which is more or less of circular shape, and its associated slopes generally steepened may play a major role in the dynamics of geomorphic processes mainly associated with water. The watershed medium is defined as “the area that receives rainfall whereby hydrological processes may result in losses and delays towards an outlet (Bendjoudi, 2002). In addition to the climatic conditions that would be regarded as a triggering factor of geomorphic processes, physical characteristics of watershed influence the hydrological budget and temporal distribution of flows and associated sediment loads (Bendjoudi, 2002). These characteristics involve topography, geology, land type, but also the rainfall intensity and the shape of the watershed that influences the flow patterns of rainfall (Strahler, 1952).

## 4.2 Physical and chemical properties of soils of mined sites

### 4.2.1 Distribution of soil properties on different mines

The locations of sample sites of the two studied mines are indicated in the previous chapter. Table 13 gives an overview of soil texture classes on the studied mines; it as well include the bulk density (BD), total porosity (TP), soil organic matter content (OM) and soil stable aggregates (SSA). In this section OM and SSA are more described than BD and TP porosity which are presented in the next section together with other measured variables on the topsoil layer. The percentages by weight of sand, silt and clay of studied soils of Gatumba mines were used to assign them a specific textural class. All soils have clayey texture on both depths (0-30 cm and 30-60 cm). Generally the distribution of soil texture represent 24 to 41 % clay, 17 to 26 % silt and 34 to 53% sand; and soils were categorized as clay loam, and sandy clay loam.

**Table 13:** Soil texture classes on the studied mines

Major Mine Site	Location (local name)	Depth	Average Soil texture (%)			BD	TP	OM	SSA	Soil Class	Textural
		Cm	Clay	Silt	Sand	(gcm <sup>-3</sup> )	(%)	(%)	(%)		USDA
Gatare	Gatare 1	0-30	37.8	18.7	43.4	1.3	43	1.5	7.5		clay loam
		30-60	39.9	17.9	42.2	-	-	1.1	7.3		clay loam
	Gatare 2	0-30	24.0	22.0	53.8	1.5	34	1.4	7.9		sandy clay loam
		30-60	44.0	22.0	34.0	-	-	1.5	8.2		clay loam
Ruhanga	Ruhanga (1)	0-30	32.8	21.7	45.5	1.4	33	2.3	8.6		clay loam
		30-60	35.7	20.5	43.7	-	-	1.7	9.9		clay loam
	Ruhanga (2)	0-30	24.2	26.0	49.7	1.3	52	2.3	9.5		sandy clay loam
		30-60	30.3	22.0	47.7	-	-	1.8	8.9		sandy clay loam

Clay<0.002mm, Silt>0.002 mm and <0.05 mm, Sand >0.05 and <2mm

The percentages by weight of sand, silt and clay of studied mines were used to assign them a specific texture classes. Except soils of Gatare which are more or less sandy on some few locations (loamy Sand or sandy Loam, which ranges from of 16-28 % clay, 9-34 % silt and 50-82 % sand), all other locations of both Ruhanga and Gatare mines exhibit clayey soils on both depths (0-30 cm and 30-60 cm), ranging from 28 to 41 % clay, 14 to 27 % silt and 35 to 52% sand. The triangular texture diagram classifies them as Clay, Clay loam or Sandy clay loam. High sand content in soils of Gatare on some locations could probably have been resulted from water erosion which removed fines or the underlying parent material.

Analyses show that soil texture with mines doesn't differ much from that of control sites. The soil texture within experimental plots on both surface and depths are more or less homogeneously distributed, except some slight differences. The clay content is slightly elevated in the subsoil with less silt. Although OM seems to be slightly higher in the topsoil, the subsoil exhibits a relatively elevated stability of aggregates.

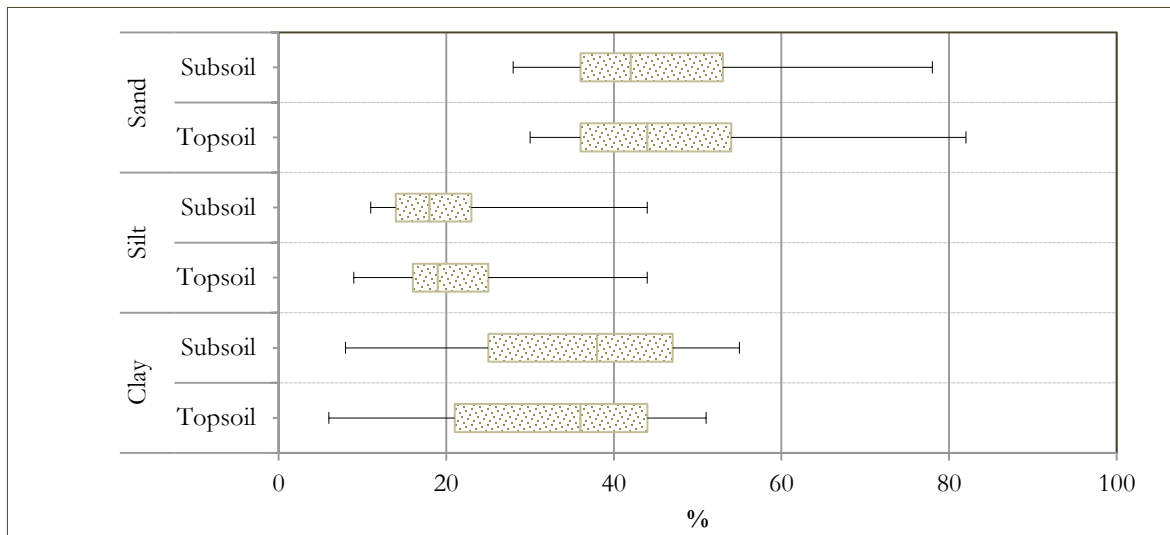
The Differences have been found in BD and TP variables over the studied plots. The mean values in topsoil layers range from 1.30 to 1.50 g cm<sup>-3</sup> and 33 to 52 % for BD and TP respectively. However, if we compare values from different plots, Control Sites (outside of mine influence) and Ex-mine Cultivated Sites present lower values of BD and TP which range from 1.29 to 1.53 g cm<sup>-3</sup> and from 41 to 49 % respectively. BD of the studied soils present elevated values than those which would be expected for our soil texture classes. Ideal bulk densities for plant growth according to USDA-NRCS (2010) should not exceed 1.30gcm<sup>-3</sup>(USDA-NRCS, 1999).Table 14 summarizes the statistical outputs of analysed soil properties of both topsoils and subsoils.

**Table 14:** Statistical outputs of soil texture, OM and SSA in topsoil layer and subsoil layer of mines

Sta. Param	Topsoil (0-30cm)					Subsoil (30-60cm)				
	Clay (%)	Silt (%)	Sand (%)	OM (%)	SSA (%)	Clay (%)	Silt (%)	Sand (%)	OM (%)	SSA (%)
Mean	31.94	21.03	47.03	1.77	8.11	34.94	19.58	45.48	1.46	7.95
Std. Dev	2.55	1.36	2.23	0.15	0.50	2.51	1.29	2.15	0.10	0.53
Median	36.00	19.00	44.00	1.62	9.22	38.00	18.00	42.00	1.47	8.10
Std. Error	14.66	7.79	12.83	0.86	2.86	14.40	7.41	12.34	0.55	3.07
Sample Variance	215.06	60.72	164.53	0.75	8.17	207.50	54.88	152.38	0.31	9.43
Kurtosis	-1.04	1.76	0.58	2.23	-0.34	-0.92	2.64	0.16	-0.83	-0.63
Skewnis	-0.52	1.25	0.92	1.16	-0.38	-0.55	1.47	0.86	0.20	0.01
Range	45.00	35.00	52.00	4.03	12.27	47.00	33.00	50.00	1.91	11.79
Minimum	6.00	9.00	30.00	0.57	0.7	8.00	11.00	28.00	0.64	1.84
Maximum	51.00	44.00	82.00	4.60	13.04	55.00	44.00	78.00	2.55	13.64
Confidence Level	5.20	2.76	4.55	0.31	1.01	5.11	2.63	4.38	0.20	1.09

N: 34/34

The Figure below captures the distribution of soil variables given in the table above.

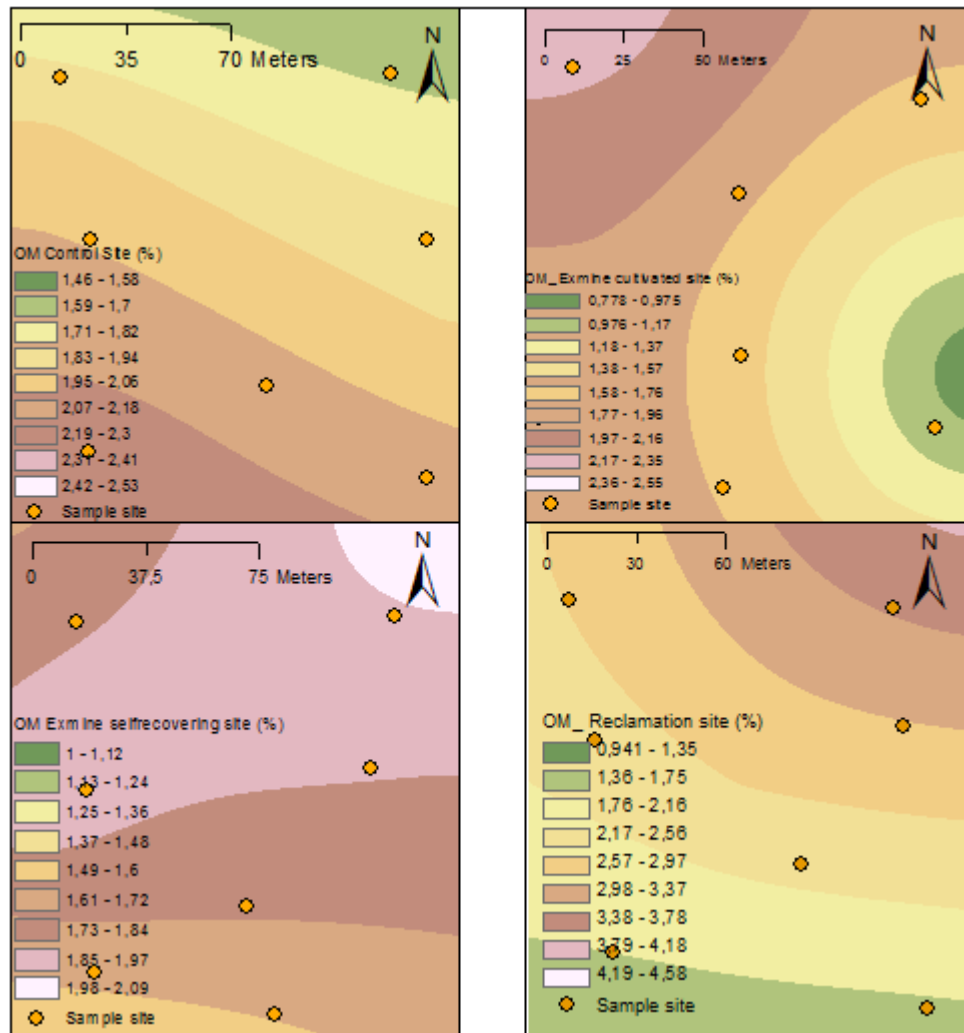
**Figure 23:** Distribution of soil texture in topsoil and subsoil layers

The Box and Whisker Plot (Figure 23) indicate the following:

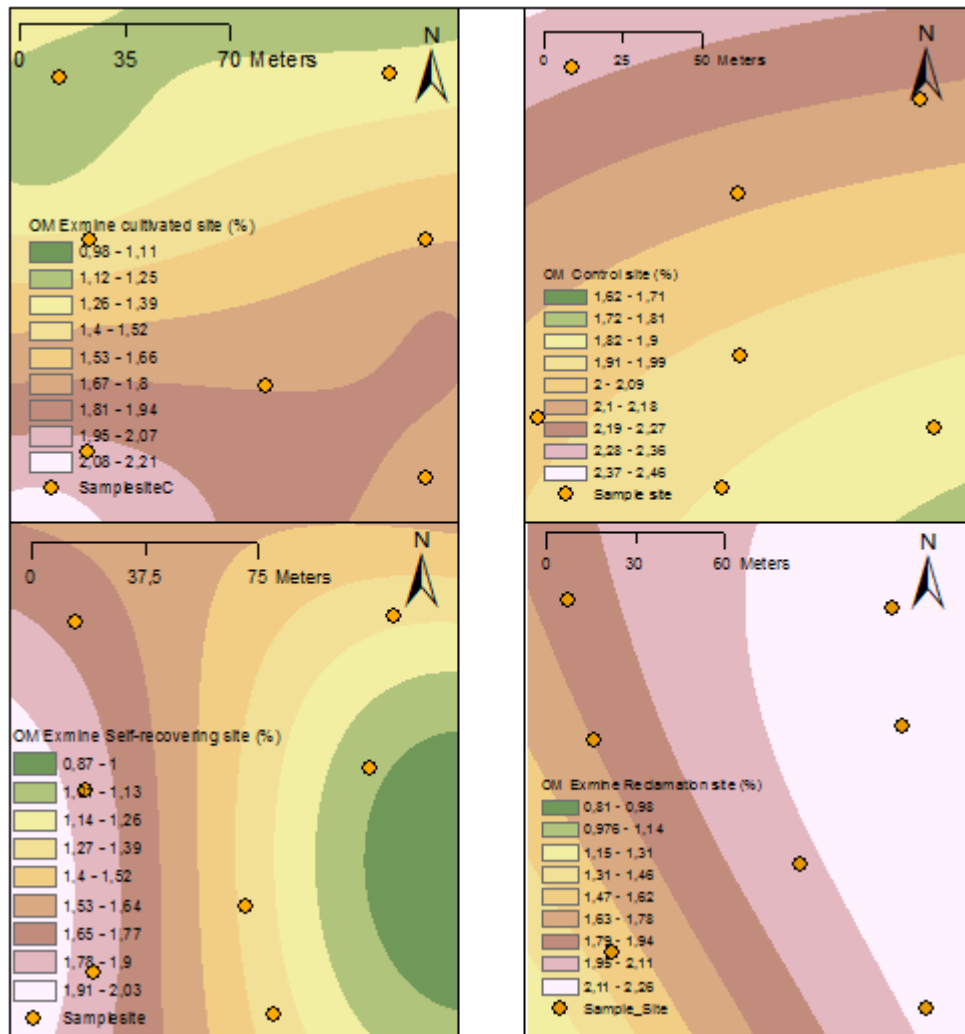
- 75% of clay ranges between 22 and 44% for topsoil, and slightly elevated in subsoil soil layers, with 25 to 47 %). Clay on both layers is much more skewed left while silt and sand are skewed right.
- The distribution of sand on both soil layers is relatively in the same ranges (between 35% and 55% in average), whereas silt is slightly elevated in topsoil layer.

As soil texture on both mines and control sites are more or less of the same ranges, soils did differ however in their OM and SSA. Topsoil of different land uses showed a relatively high OM content than subsoil layers. Reclamation site presents OM ranging from 0.91 to 4.48 %, while it comprises between 0.80 and 2.55 %; and 1 and 2.09 % on ex-mine cultivated site and ex-mine self-recovering site respectively. When compared with the OM of control site, the later doesn't exhibit more elevated OM content, the difference is mostly that OM on control site tends to be homogeneously distributed (1.5 to 2.5%).

The Figures 24-27 show the spatial distribution of OM and SSA on different land uses of Ruhanga Mine.



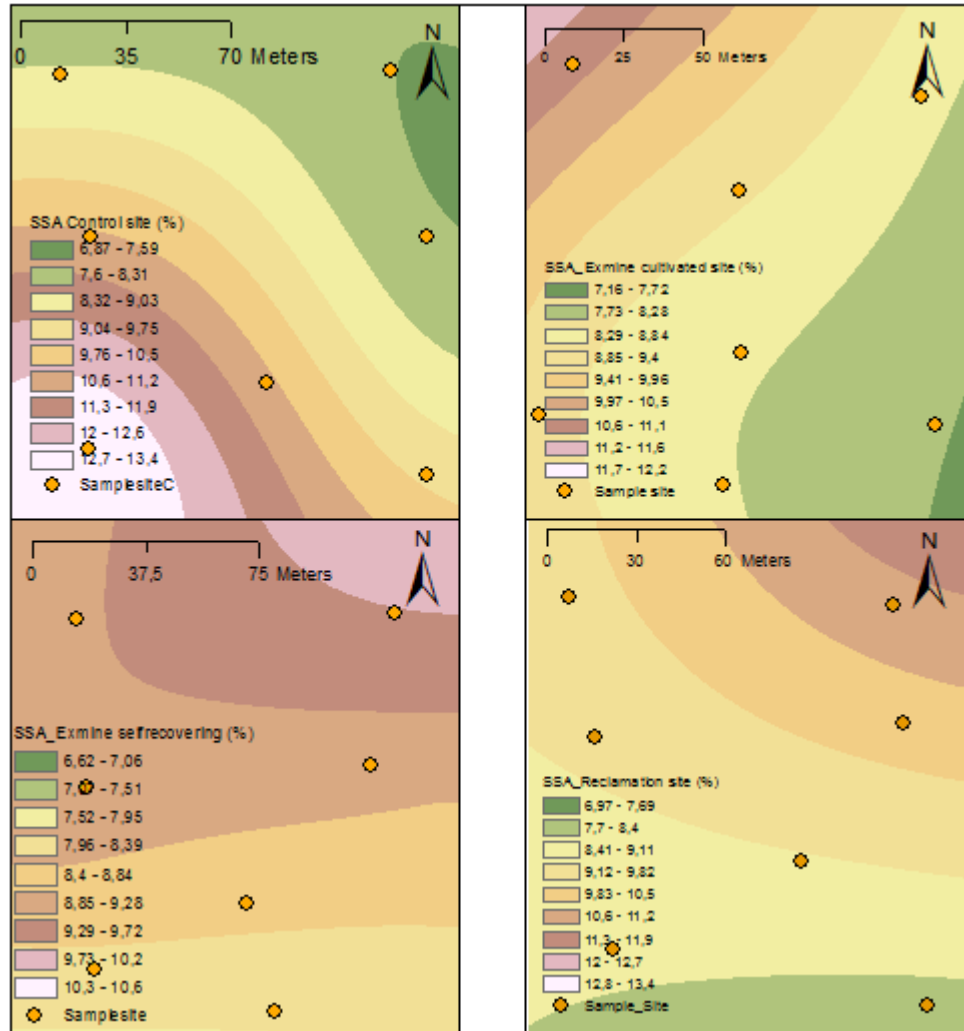
**Figure 24:** Topsoil OM content in different land uses of Ruganga Mine



**Figure 25:** Subsoil OM content in different land uses of Ruhanga Mine

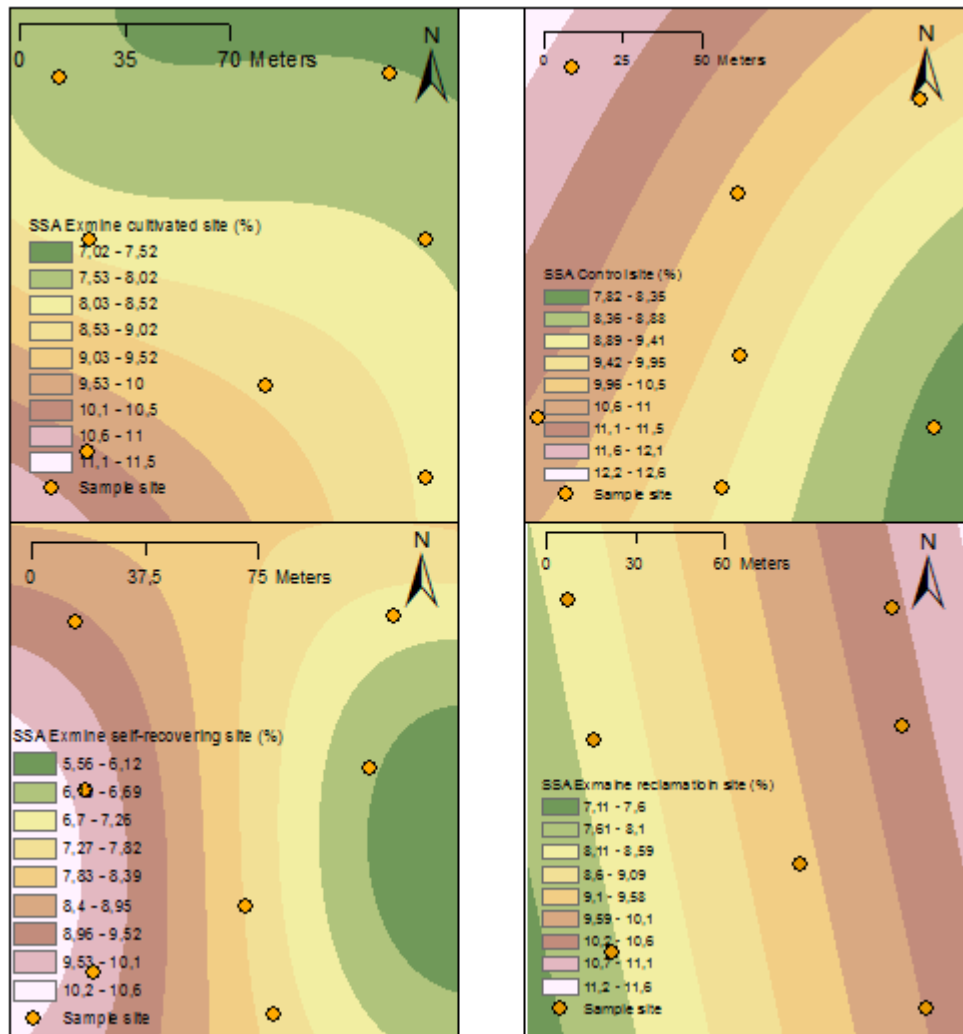
On subsoil layer, the control site shows a relatively elevated and fairly homogeneously distributed OM which comprises between 1.62 and 2.46 %, followed by ex-mine cultivated site (from 1.12 to 2.21 %). Both self-recovering site and reclamation site present similar ranges of OM comprised between 0.8 and 2.05 %. Although OM is lesser in subsoil than it is in the topsoil layer, its symmetrical distribution which applies also to its associated SSA shows a relative stability reflected by a homogeneous distribution, contrary to topsoil where the dissymmetric distribution of boxes and whiskers might show variation in distribution.





**Figure 26:** Topsoil SSA content in different land uses of Ruhanga Mine

Generally, the mean range of SSA of Ruhanga topsoils comprises between 6.62 % and 13.40 %. However they are variably distributed over different land uses identified in the mine sites. Reclamation site and control site present a relatively the same percentage of distribution which ranges from 6.97 % to 13.40 %. The rating of SSA in other sites is low; they fall within the range of 6.62 and 10.60 % on ex-mine self-recovering site; and 7.16% and 12.20 % on ex-mine cultivated site. SSA of subsoil layers comprises between 5.55 % and 12.60 %. Despite of the low content in subsoil layers over all land uses, control site followed by reclamation site have SSA between 7.82 and 12.60 % and 7.11 and 11.60 % respectively.



**Figure 27:** Subsoil SSA content in different land uses of Ruhanga Mine

Topsoil OM and SSA contents in different land uses of Gatare Mine are presented on Figures 28-29. Only reclamation land class is not presented for this mining site. Similarly to Ruhanga mine land uses, OM content and SSA rates are more elevated in topsoils than in subsoils. Values of OM are in the range of 1.46 and 2.49 % for topsoil of control site, while they are between 0.9 and 2.31 % and 1.28 and 2.33 % for ex-mine self-recovering site and cultivated site respectively. SSA values comprise between 7% and 12.60%. The more elevated SSA is found on control site, with the upper limit of 12.60 %, followed by the cultivated site (12.20 %) and the ex-mine self-recovering site (11.30 %).

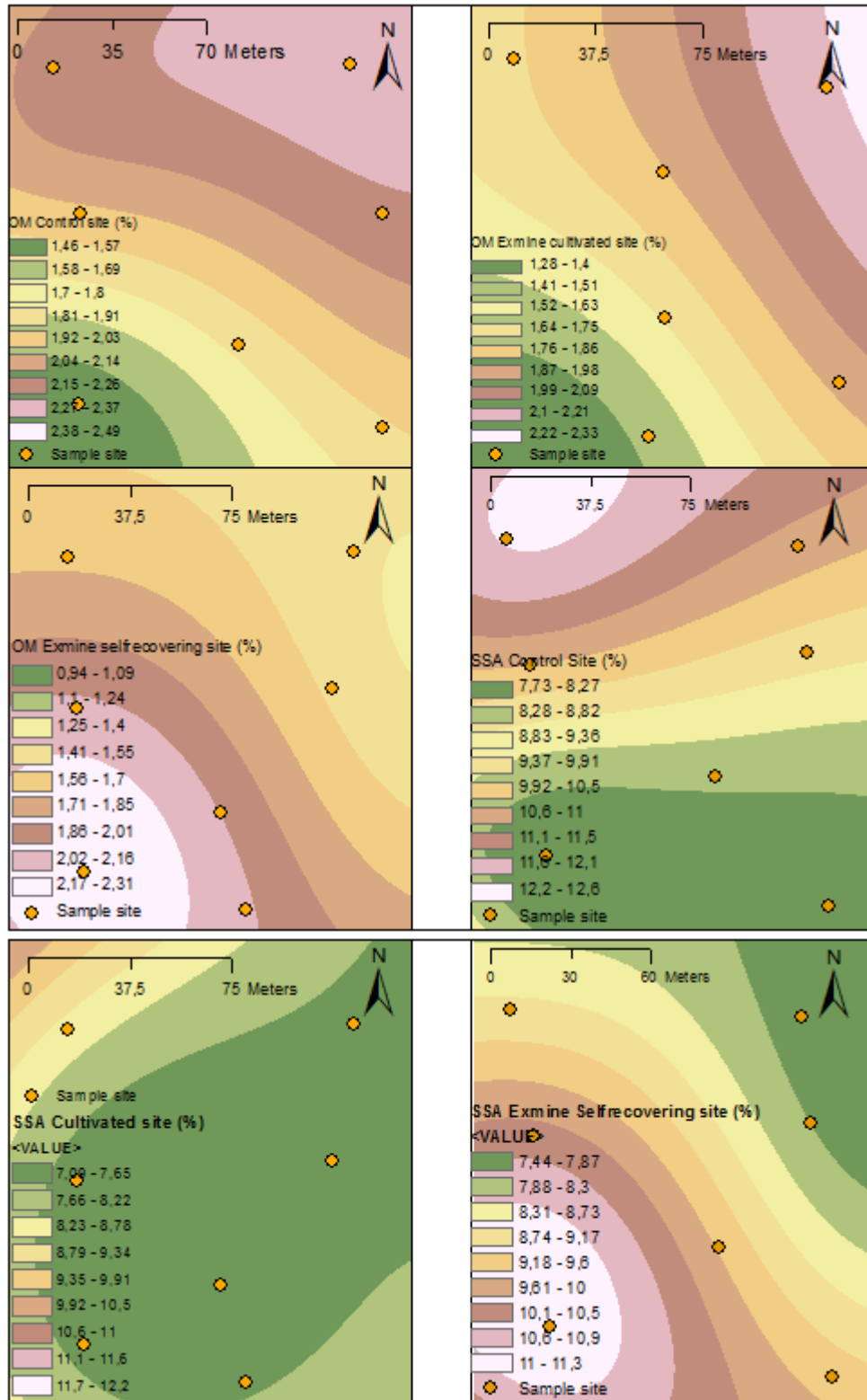


Figure 28: Topsoil OM and SSA in different land uses of Gatere Mine

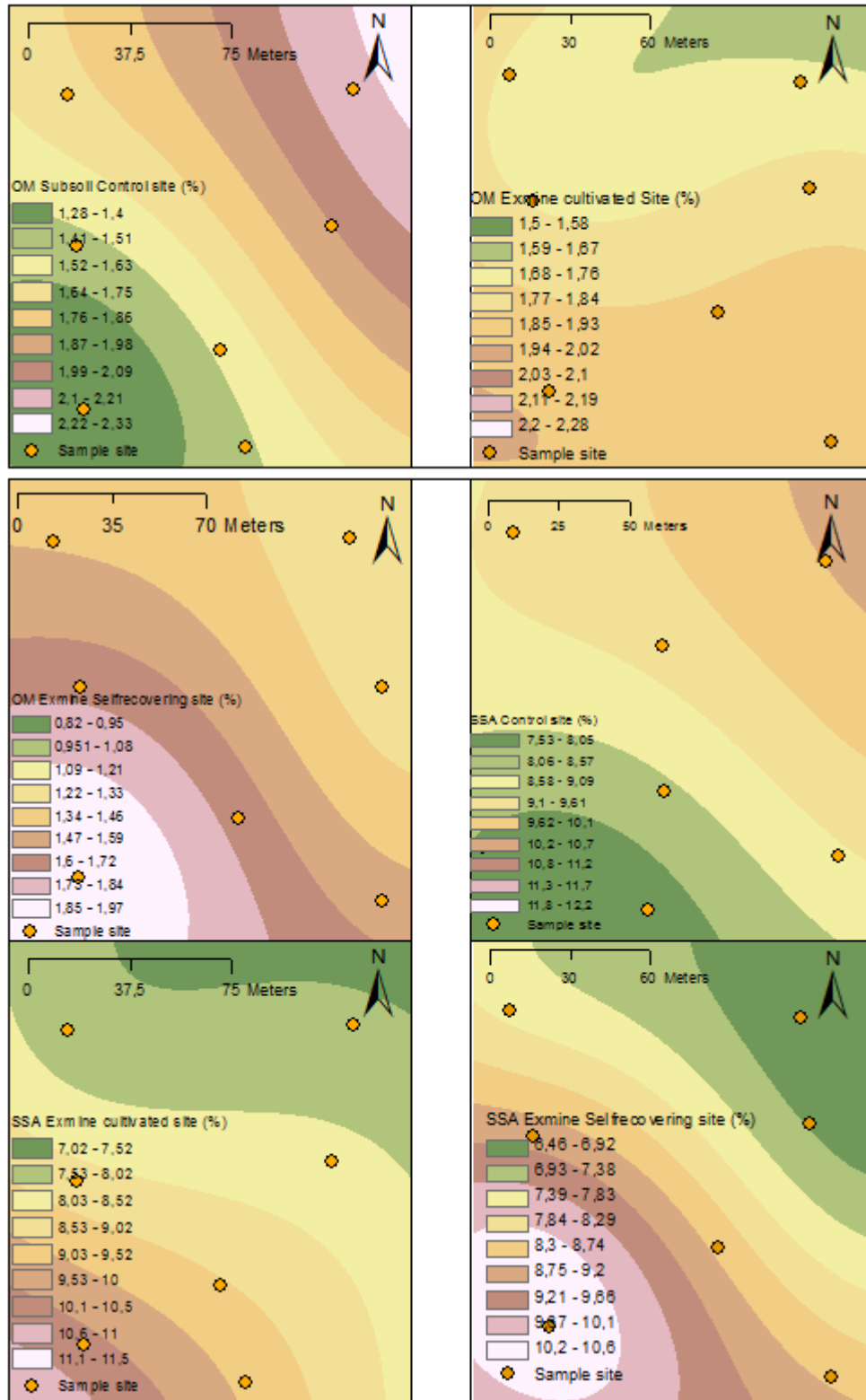
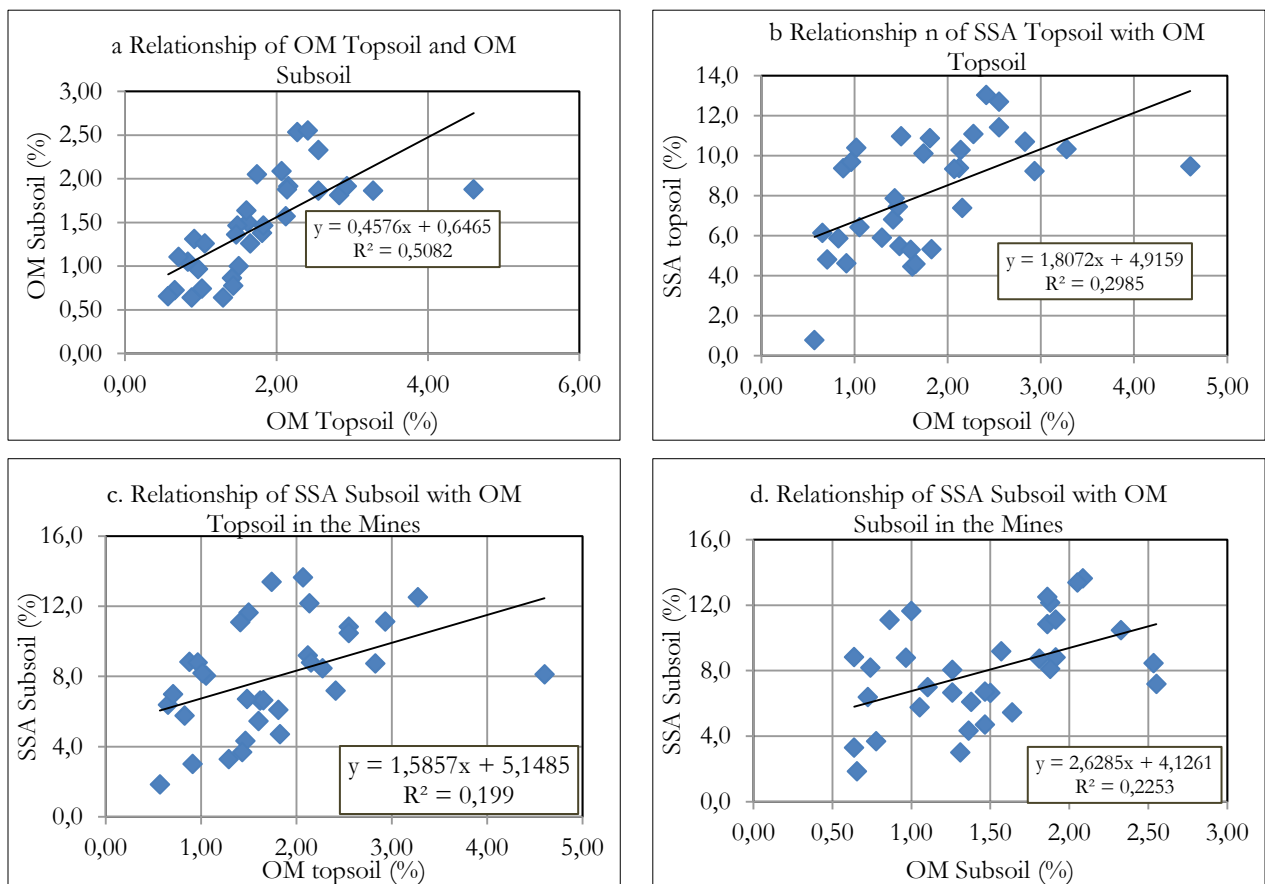


Figure 29: Subsoil OM content in different land uses of Gatare Mine

The subsoil OM ranges from 0.75 to 2.33 %. Control site and cultivated site have higher values, from 1.28 to 2.33 % while its content on self-recovering site is in the range of 0.75 and 1.97 %. This distribution shows that OM tends to be equally distributed on both control and cultivated sites, whereas observed variability in distribution could be associated with variability in degradation or reconstitution of soil. SSA is in the range of 6.46 and 13.40 %. Aggregation ratings are generally low and variably distributed in all studied mines. On control site it ranges between 7.53 and 12.20 %, and between 7.02 and 11.50 % on ex-mine cultivated site. Values on ex-mine self-recovering site are between 6.46 and 10.6 %.

Several authors have used soil quality indicators which change with land use condition (e.g. OM and SSA) that can be easily measured (Larson & Pierce, 1994). The level of correlation also has been useful to evaluate the disturbance induced by land uses (Tisdall & Oades, 1982). In the same line, the plotting of OM and SSA results of both soil (Figure 30) enabled to compare the two soil variables and to understand the level of disturbance.



**Figure 30:** Variation of SSA with OM in the topsoil and subsoil layers

As it can be seen in (Figure 30) above, OM and SSA within the same soil layer and or on both soil layers are positively correlated, but the correlation is relatively high between OM of topsoil and OM of subsoil (Figure30a) This implies that increase in topsoil OM will increase subsoil OM. BD was selected as dependant variable in relation with those presented in the table below. Regression estimates between BD as a dependent variable with other selected independent variables ones are presented below Table 15. At  $P \leq 0.05$ , the correlation was found to be not significant probably because of the disturbance of the studied sites. Of all the independent variables of topsoils, OM seems to have a stronger influence on the bulk density than other soil properties.

**Table 15:** Correlation and regression analysis of BD with selected soil properties

Correlation and regression analysis of BD with selected soil properties			
Topsoil Mines	Regression line	P_Value	Significance
Clay (%)	BD= -0,0057Clay+1,5273	0,5436	NS
OM (%)	BD= -0,0981MO+1,5104	0,3688	NS
SSA (%)	BD= -0,0323SSA+1,6092	0,1524	NS
Porosity (%)	BD= -0,0052Porosity+1,5357	0,2656	NS
Multiple Regr:	$\hat{y}BD=1,7083+0,0063Clay+0,1373OM-0,0400SSA-0,0126377TP$		

#### 4.2.2 Soil properties of control sites

The Table 16 summarises the statistical outputs of analysed soil variables. The BD and PAWC were selected as dependent variables to study their relationship with explanatory soil variable once within the Control Sites and in mines as well.

**Table 16:** Statistical outputs of mean values of analysed topsoil samples on control sites

Statist. Parameters	Clay (%)	Silt (%)	Sand (%)	OM (%)	SSA (%)	BD (gcm <sup>-3</sup> )	TP (%)	WHC (%)	PWP (%)	AWC (%)	PAWC (%)
Mean	34.44	20.29	45.25	1.84	8.63	1.33	39.77	18.19	15.93	2.26	90.79
Std. Dev	3.80	0.59	3.36	0.22	0.79	0.03	4.41	2.04	2.07	0.18	8.69
Median	36.67	20.75	42.90	1.80	9.17	1.31	40.75	20.20	18.05	2.15	87.21
Std. Error	10.06	1.55	8.89	0.58	2.10	0.09	11.66	5.40	5.47	0.47	22.99
Sample Variance	101.10	2.40	79.00	0.34	4.41	0.01	136.03	29.13	29.95	0.22	528.63
Kurtosis	-0.69	-1.86	-0.81	-1.04	2.19	1.32	-0.36	-1.13	-0.92	-0.01	1.63
Skewnis	-0.84	-0.10	0.79	-0.05	-1.44	0.46	-0.80	-0.74	-0.77	0.62	1.23
Range	27.35	3.87	23.90	1.57	5.97	0.28	31.50	13.69	14.50	1.39	67.49
Minimum	18.60	18.33	35.30	1.11	4.50	1.20	20.00	10.59	7.56	1.64	67.06
Maximum	45.95	22.20	59.20	2.68	10.47	1.48	51.50	24.28	22.06	3.03	134.55
Confidence Level	9.30	1.43	8.22	0.54	1.94	0.08	10.79	4.99	5.06	0.43	2126

N: 7/7

OM: soil organic matter content, SSA: soil stable aggregate, TP: total porosity, WHC: water holding capacity.

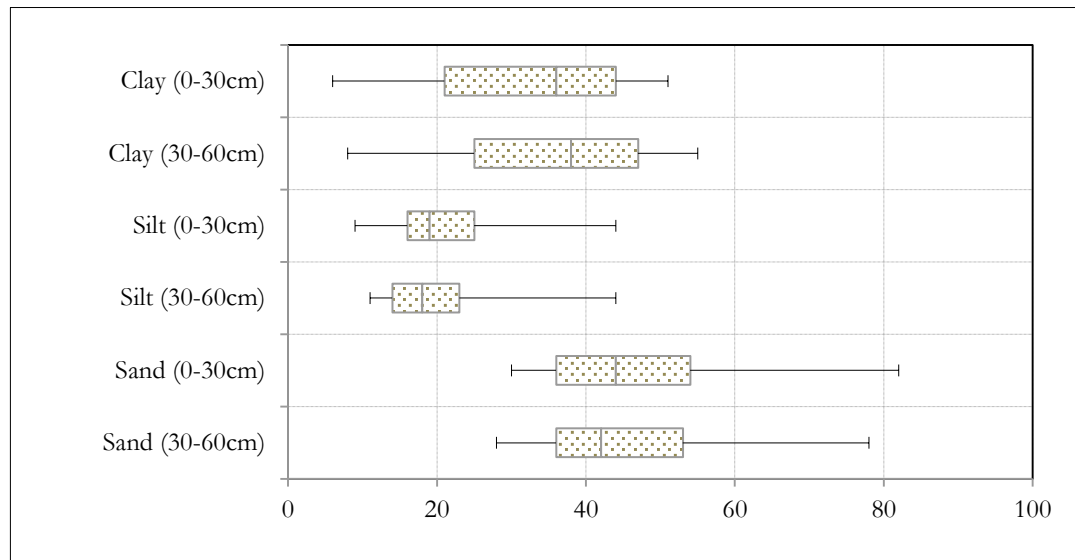
Table 17 below indicates the correlation between soil variables on control sites.

**Table 17:** Relationship between soil variables of control sites

Soil Parameter	Clay (%)	Silt (%)	Sand (%)	OM (%)	SSA (%)	TP (%)	WCH (%)	PWP (%)	AWC (%)	PAWC (kL/ha)	BD (gcm <sup>-3</sup> )
Clay (%)	1										
Silt (%)	-0.800*	1									
	-										
Sand (%)	0.9946*	0.7322*	1								
OM (%)	0.8967*	-0.5799	-0.915*	1							
SSA (%)	0.6123*	-0.4255	-0.621*	0.7312*	1						
TP (%)	0.9608*	-0.702*	-0.967*	0.9032*	0.5524	1					
WHC (%)	0.9289*	-0.609*	-0.947*	0.9583*	0.6987*	0.9251*	1				
PWP (%)	0.9060*	-0.596	-0.922*	0.9482*	0.7332	0.899*	0.9964*	1			
AWC (%)	0.1151	-0.0509	-0.1236	-0.0390	-0.5208	0.1554	-0.1207	-0.2046	1		
PAWHC(kL/ha)	-0.1038	0.1037	0.0978	-0.2274	-0.6753	-0.0655	-0.321	-0.3981	0.972*	1	
BD (g/cm <sup>3</sup> )	-0.6704	0.4587	0.6793	-0.669*	-0.791*	-0.7021	-0.7746	-0.808	0.5168	0.706*	1

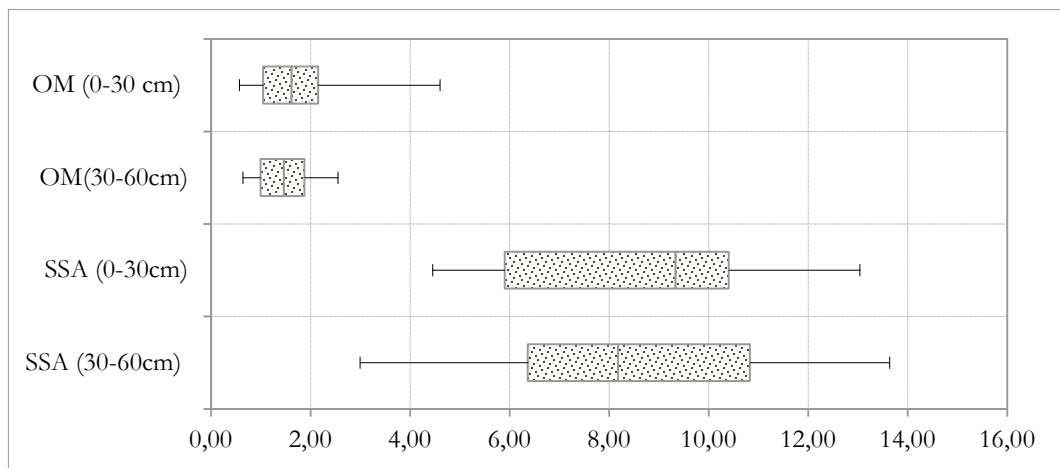
N: 14 (7/7); \* significance at P<0.05

The box and whisker Plots below have been used to find and display skews in the data, for both topsoils and subsoils. The central tendency (median) and the accompanied dispersion at the different levels of probability are presented. In a box and whisker plot, the box has lines at 25<sup>th</sup> percentile (left or bottom line depending on how the box is displayed) values, median (middle line), and 75<sup>th</sup> percentile (top line) values. Whiskers extend from each end of the box to the 5<sup>th</sup> percentile and 95<sup>th</sup> percentile respectively.



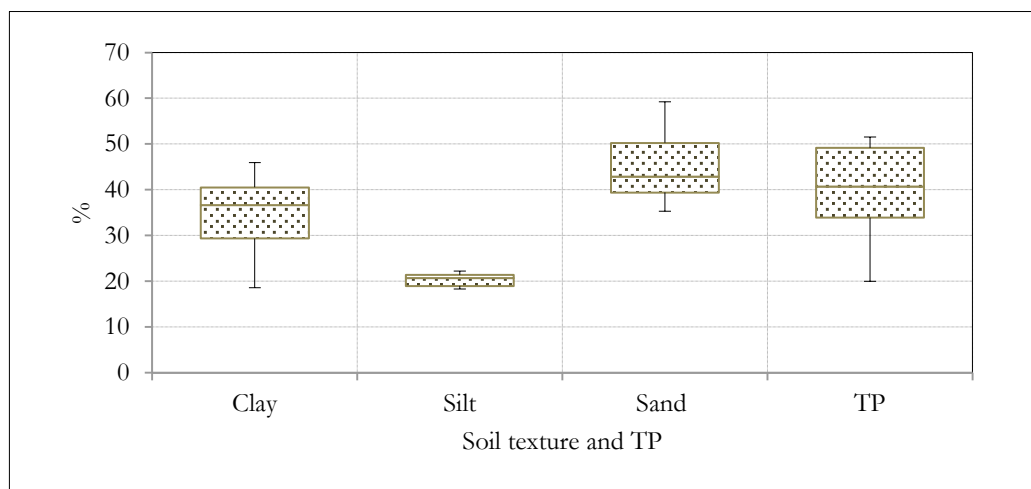
**Figure 31:** Distribution of topsoil and subsoils texture of control sites

Outliers (not presented on boxes and whisker plots below) are data with values beyond those indicated by the whiskers. The textural class of both the topsoil and subsoil horizons across all control sites (Figure 31) are more or less equally distributed. The trends of skewness follow relatively the same direction. Sand and silt are much more skewed right and silt is skewed left. The clay content is slightly elevated in the subsoil layer while the sand decreases in the subsoil horizon. The opposite is observed in the subsoils. Although the topsoil contains relatively elevated OM which is skewed right, the high rating of stability of soil aggregations (SSA) is rather observed in subsoils. However, both Figures 31 and 32 show a symmetric distribution of soil texture, SSA and OM in both soil layers suggest a good correlation between the textural classes and OM and SSA variables



**Figure 32:** Distribution of topsoil and subsoils OM and SSA of control sites

The following box (Figure 33) presents the range of soil texture and the total porosity (TP) within the control sites.



**Figure 33:** Soil texture and total porosity within the control sites



Although the figure presents the average values, the trend of results was that soils with high proportion of finer particles has lower bulk density and elevated total porosity within control sites. The simple reading of correlated soil variables as presented in Figure 35 for mines and Table 16 for the control site indicates a big difference between these two sites. The relation in control sites tends to be stronger than that of mines. This may suggest that mines are more disturbed, but this will be discussed in the next section.

#### 4.2.3 Relationship of soil variables in topsoil layer of mines

The statistical outputs of the analysed topsoil are presented in table 17. Given that BD, TP and Water Holding characteristics were measured on topsoils of selected sites, the table as well summarises the major outputs of analyzed soil variables of these specific locations, which will be more developed in the following section.

**Table 18:** Statistical outputs of analysed topsoil samples with BD, TP and WHC

Stat. Parameter	Clay (%)	Silt (%)	Sand (%)	OM (%)	SSA (%)	BD (g/cm <sup>3</sup> )	TP (%)	WHC (%)	PWP (%)	AWC (%)	PAWC (kL/ha)
Mean	33.70	20.55	45.75	1.86	8.27	1.35	40.60	19.46	16.98	2.48	100.83
Std. Dev	2.90	1.67	3.04	0.22	0.68	0.02	2.44	1.19	1.19	0.22	9.32
Median	34.50	19.00	42.00	1.68	9.38	1.33	43.50	21.07	18.67	2.17	87.57
Std- Error	12.97	7.45	13.60	0.99	3.04	0.10	10.93	5.33	5.31	0.99	41.70
S. Variance	168.22	55.52	184.93	0.98	9.23	0.01	119.41	28.45	28.20	0.97	1739.09
Kurtosis	-0.20	4.34	2.22	1.65	0.22	-0.37	0.45	-0.57	-0.17	4.11	4.09
Skewnis	-0.69	1.52	1.56	1.09	-0.83	0.50	-1.08	-0.62	-0.67	1.89	1.98
Range	45.00	35.00	50.00	4.03	11.92	0.38	39.00	17.60	19.93	3.99	165.52
Minimum	6.00	9.00	32.00	0.57	0.77	1.18	15.00	9.67	5.41	1.54	61.78
Maximum	51.00	44.00	82.00	4.60	12.70	1.56	54.00	27.27	25.34	5.53	227.30
Conf. Level	6.07	3.49	6.36	0.46	1.42	0.05	5.11	2.50	2.49	0.46	19.52

The graphs below show the relationship between BD and TP as dependent variables with other measured soil variables with the topsoil layers of mine sites. It could be deduced easily that there is a strong relationship between BD, TP (dependent variables) and clay, but this relationship is not significant with other soil properties indicated in Figure 34 and Table 17. The BD is positively correlated with sand and silt but for the later the relationship is not significant. And it is similar to BD and OM as well as TP and OM. The obtained negative significant is in correlation with decreasing BD as Clay increases, and TP which decreases at increasing BD.

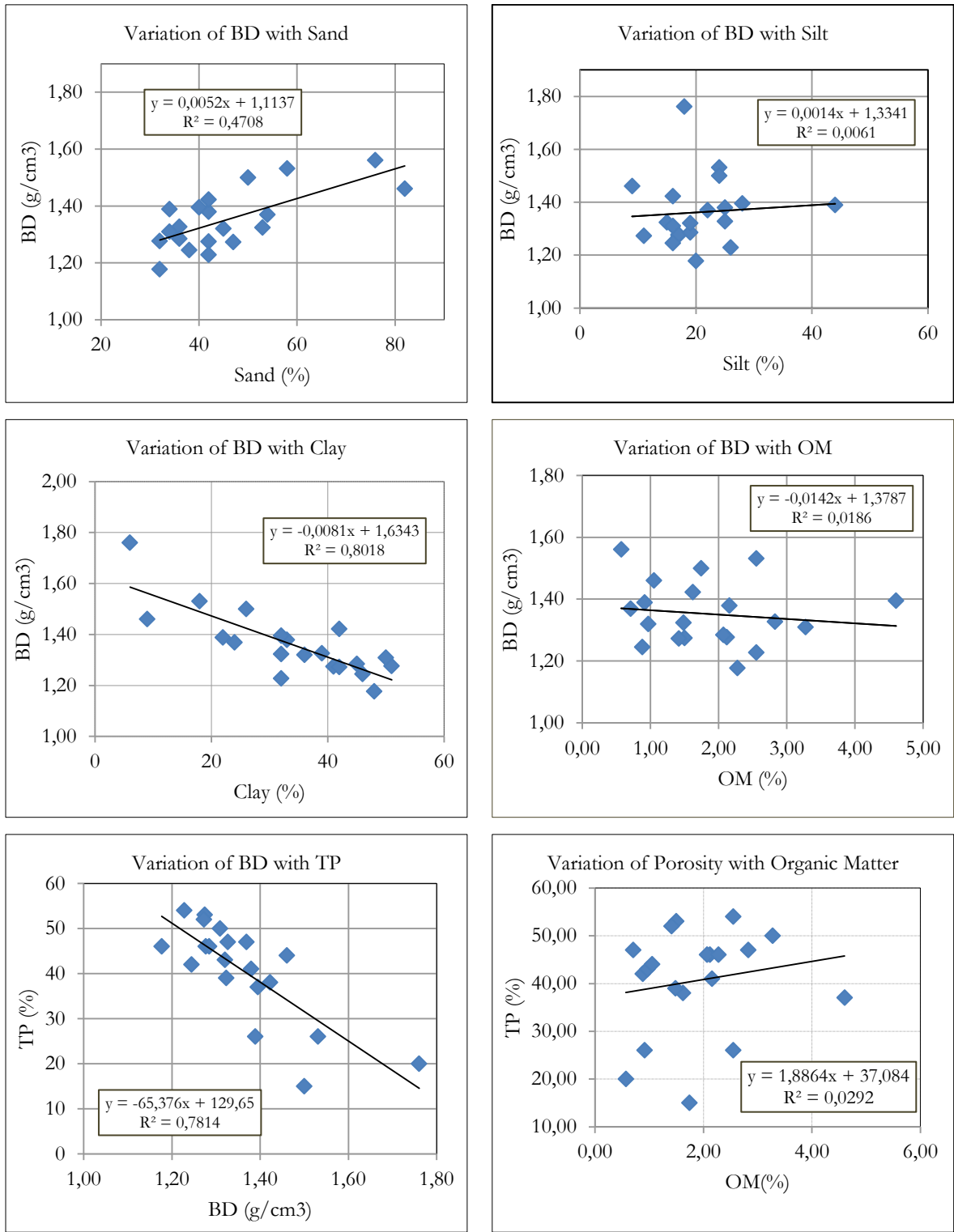


Figure 34: Relationship of BD and TP with other soil variables within topsoils of mine sites

**Table 19:** Relationship between soil physical and chemical properties for investigated topsoil of mines

	Clay (%)	Silt (%)	Sand (%)	O.M (%)	SSA (%)	TP (%)	WHC (%)	PWP (%)	AWC (%)	PAWHC (kL/ha)	BD (gcm <sup>-3</sup> )
Clay (%)	1										
Silt (%)	-0.2008	1									
Sand (%)	-0.8437	-0.3564	1								
O.M (%)	0.3327	0.1941	-0.4237	1							
SSA (%)	0.4972	0.0479	-0.5004	0.5750*	1						
TP (%)	0.5988	-0.3863	-0.3595	0.1710	0.3787	1					
WHC (%)	0.7089*	0.2166	0.7948*	0.4369	0.2611	0.5199	1				
PWP (%)	0.7487*	0.2517	-0.8520	0.4697	0.3109	0.4618	0.9829*	1			
AWC (%)	-0.1977	-0.1840	0.2894	-0.1667	-0.624	0.3254	0.1160	-0.0690	1		
PAWHC(kL/ha)	-0.3517	-0.1688	0.4280	-0.1997	-0.3620	0.1821	-0.0047	-0.1870	0.9825*	1	
BD	-0.8018	0.0780	0.7220	-0.2133	-0.5815	0.7814*	-0.6314	-0.6238	-0.0554	0.1256	1

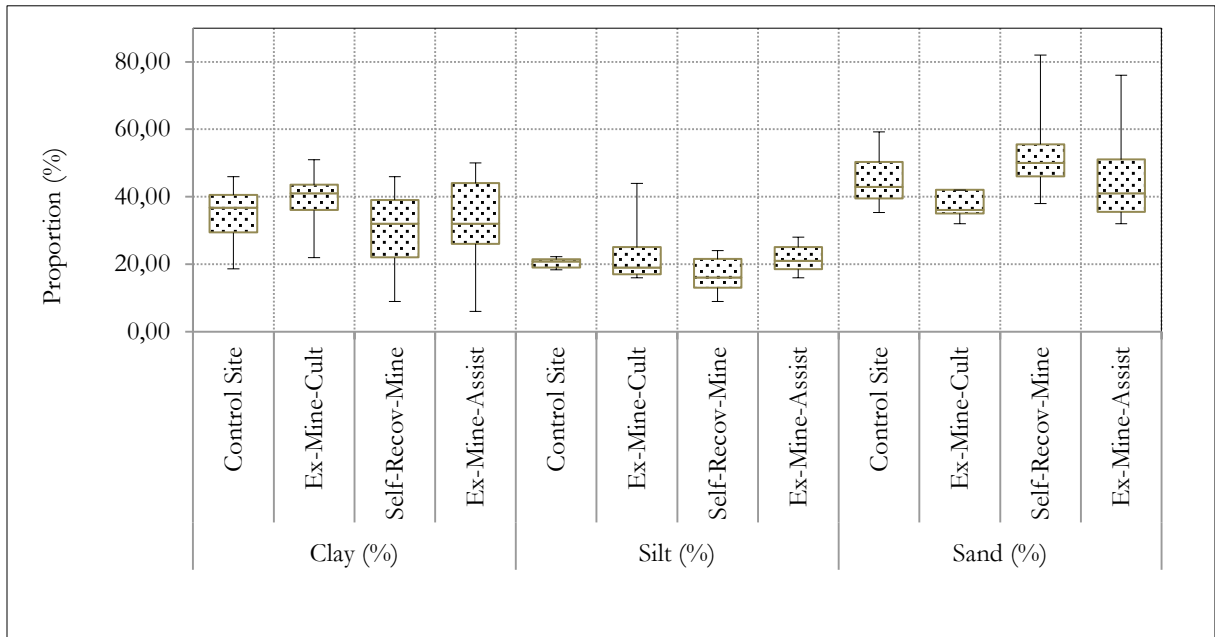
N: 20(40/2); \* significance at P<0.05, OM: soil organic matter content, SSA: soil stable aggregate, TP: total porosity, WHC: water holding capacity, PAWC: plant available water holding capacity.

As indicated in Table 18 above, clay and TP influence significantly the BD whereas, the PAWC is much more influenced by clay and OM.

#### 4.2.4 Comparison of soil parameters of different land uses within the mine sites

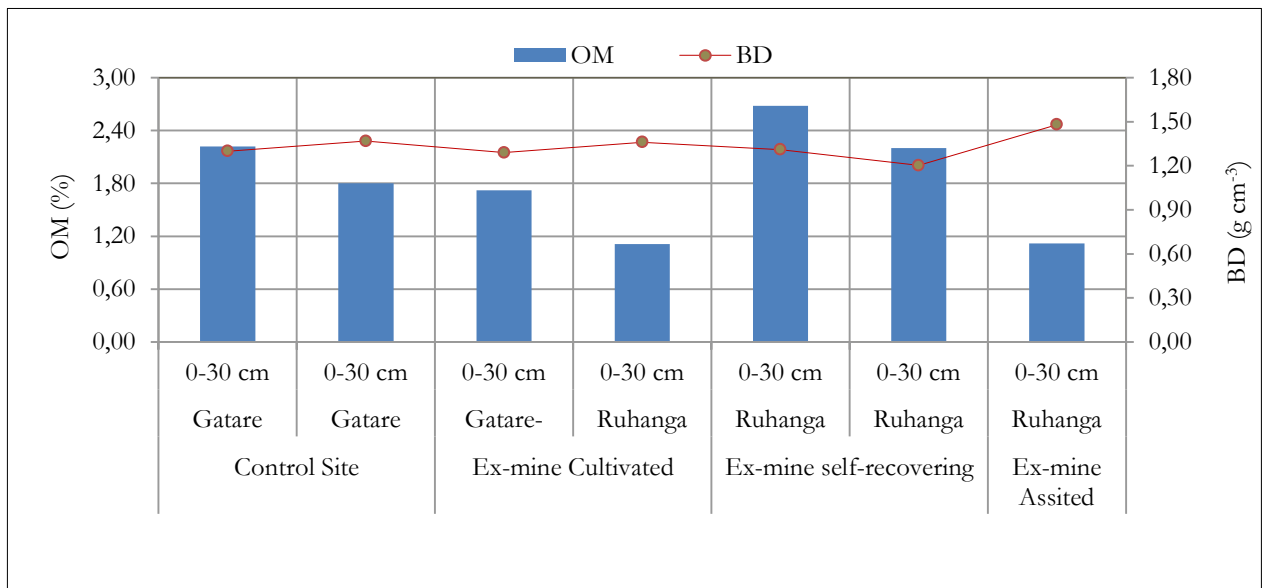
The Figure below presents the soil texture in individual mine plots and control site. There is not much variation in texture distribution for all sites including control site. The silt content is more or less 20%, whereas the clay is relatively concentrated between 30 and 40% but skewed left. The sand skewed right, plots close 40% and more, except for ex-mine cultivated site skewed left. This makes soils to fall in the closest textural classes as by soil texture triangle.

As shown in Figure 36, soil textures are not symmetrically distributed. The Box and whisker plots are more skewed left for clay and more right for sand. Silt is more skewed right for ex-mine cultivated site but it is relatively equally distributed on other experimental plots

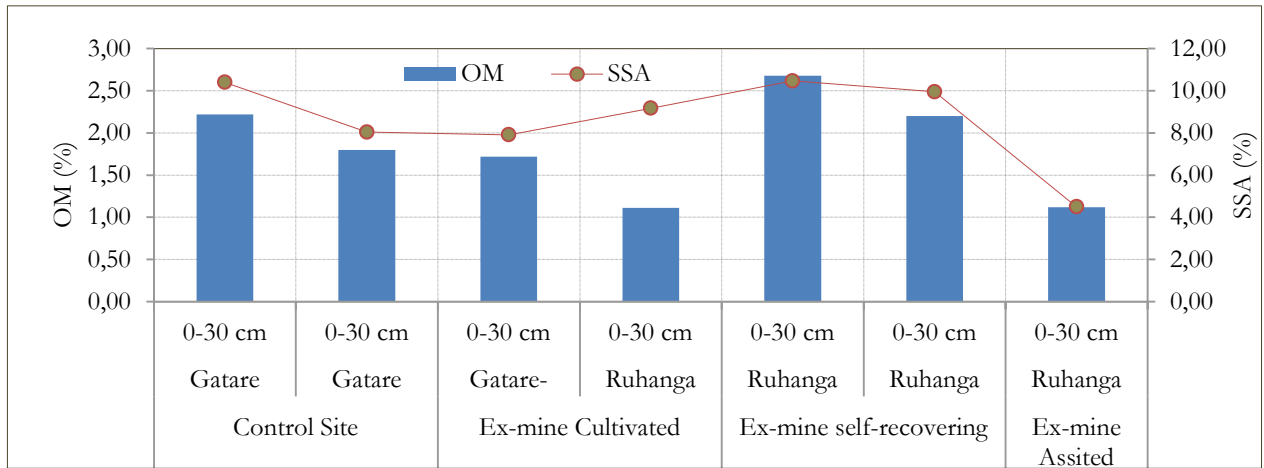


**Figure 35:** Distribution of soil texture in mines and control sites

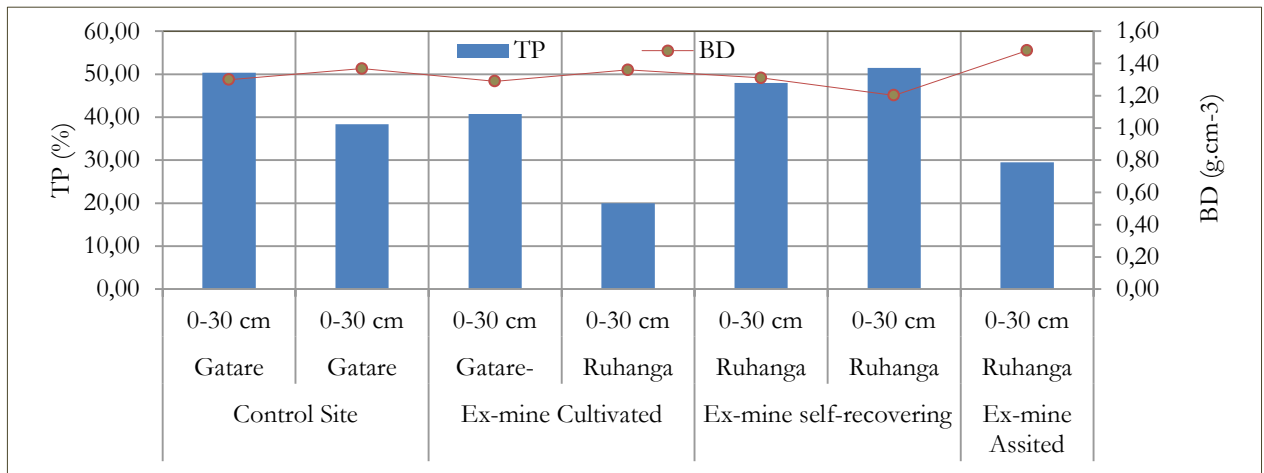
By proportion the average of OM content is more elevated in Ex-mine reclamation plot (1-3 %), followed by that of control sites (2 %). The average value of OM on both Ex-mine cultivated and self-recovering sites is less or equal to 2 %. There was not big difference of BD among these plots, except that control site and cultivated plot tend to have lower BD than ex-mine reclamation and ex-mine self-recovering sites.



**Figure 36:** Organic matter and bulk density in the respective plots



**Figure 37:** Organic matter and SSA in the respective plots



**Figure 38:** TP and BD in the respective sites

Analysis showed that 75 % of SSA average values over all studied sites ranges within  $\leq 10$  %, while only 25 % are slightly higher than 10 %. All samples fall in the category of very low to low rating. No sample attained the moderate or high rating suggested by Hazelton and Murphy (2007) that are stable to wetting as shown in Table 19. Except Ex-mine reclamation sites which are skewed more left, all other sites Boxes indicate 100 % of SSA above 5 %.

**Table 20:** Rating of soil stable aggregates (Hazelton and Murphy, 2007)

1-2mm stable aggregates (%)	Rating
<10	Very low
10-20	Low
20-30	Moderate
>30	High

50 % of TP for all sites is within the range of 52 and 30 %, but percentages drop more to lower values since the whisker plots for all sites are much skewed left up to 15. This large skewness to lower values

indicates a spatial variability in TP distribution. The ex-mine self-recovering sites present slightly lower values of TP if we compare it with the other plots, probably because TP for the latter is improved by cultivation, manure or amendment by human.

#### 4.2.5 Water holding characteristics and infiltration

The water holding characteristics of Gatumba mines were studied based on analysed soil samples, together with results of field experiment for infiltration. Both results are presented consecutively in the next sections.

##### 4.2.5.1 Water holding characteristics

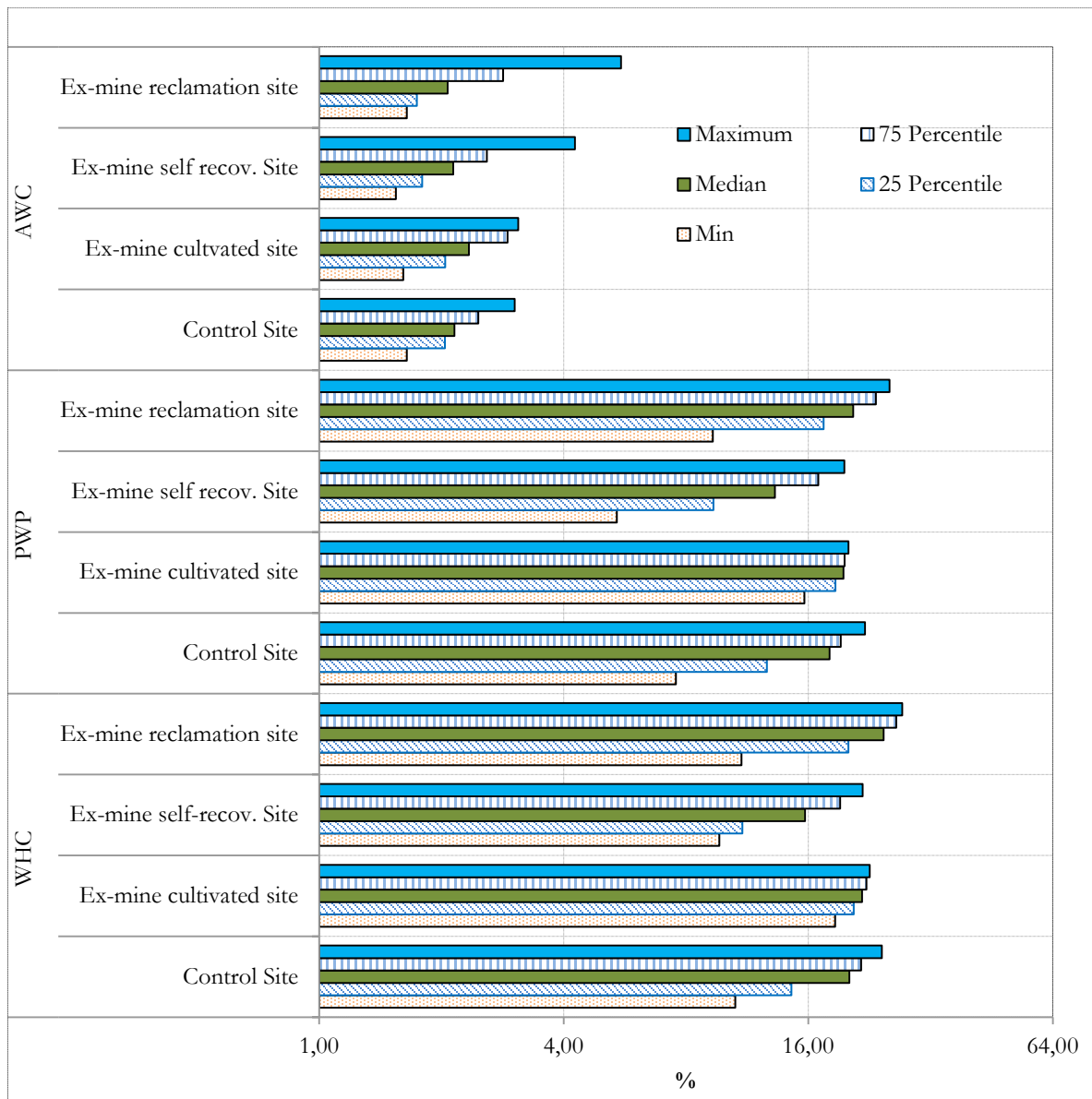
Results of water holding capacity are presented in Table 21 below:

**Table 21:** Soil and water holding characteristics of different mine sites

Site	Clay	Silt	Sand	OM	SSA	TP	WHC	PWP	AWC	PAWC
	%	%	%	%	%	%	%	%	%	kL/ha
Control Site	45.95	18.63	35.30	2.22	10.40	50.33	21.04	18.32	2.71	104.88
	36.67	18.33	45.00	1.80	8.04	38.33	18.14	16.00	2.14	87.74
	36.20	20.90	42.90	1.72	7.91	40.75	20.20	18.05	2.15	8392
	18.60	22.20	59.20	1.11	9.17	20.00	10.96	9.32	1.64	95,00
	40.75	20.75	38.50	2.68	12.47	48.00	24.28	2,06	2.22	87.21
	40.33	19.33	40.33	2.20	9.95	51.50	22.13	2,19	1.94	70,5
	22.58	21.91	55.50	1.12	8.50	29.50	10.59	7.56	3.03	134.5
Ex-Mine- Cultivated plot	41.00	17.00	42.00	1.50	10.97	53.00	18.62	15.67	2.95	112.91
	51.00	17.00	32.00	2.12	9.38	46.00	22.39	19.53	2.86	109.73
	33.00	25.00	42.00	2.16	7.38	41.00	22.65	19.56	3.09	127.83
	39.00	25.00	36.00	2.83	10.70	47.00	22.11	19.78	2.34	93.03
	45.00	19.00	36.00	2.07	9.34	46.00	21.71	20.10	1.61	62.06
	42.00	16.00	42.00	1.62	4.45	38.00	20.76	18.64	2.12	90.53
	22.00	44.00	34.00	0.91	4.63	26.00	20.66	18.70	1.96	81.86
Ex-Mine Self_Recov	46.00	16.00	38.00	0.88	9.37	42.00	21.37	19.58	1.79	66.81
	36.00	19.00	45.00	0.97	9.70	43.00	21.76	19.63	2.14	84.60
	42.00	11.00	47.00	1.41	6.81	52.00	17.01	14.29	2.72	103.73
	32.00	15.00	53.00	1.48	5.48	39.00	15.71	13.25	2.46	97.61
	9.00	9.00	82.00	1.05	842	44.00	9.67	5.41	4.26	186.78
	18.00	2,00	58.00	2.55	11.42	26.00	1053	8.99	1.54	70.92
	26.00	2,00	50.00	1.74	10.11	15.00	11.50	9.70	1.80	80.87
Ex-Mine Assist plot	48.00	20.00	32.00	2.28	13.09	46.00	25.37	23.15	2.21	78.11
	6.00	18.00	76.00	0.57	9.77	20.00	10.96	9.32	1.64	76.92
	32.00	28.00	40.00	4.60	9.47	37.00	26.66	23.62	3.04	127.42
	24.00	22.00	54.00	0.71	8.82	47.00	23.66	18.13	5.53	227.30
	32.00	26.00	42.00	2.55	12.70	54.00	18.89	17.22	1.68	61.78
	50.00	16.00	34.00	3.28	10.33	50.00	27.27	25.34	193	75.88

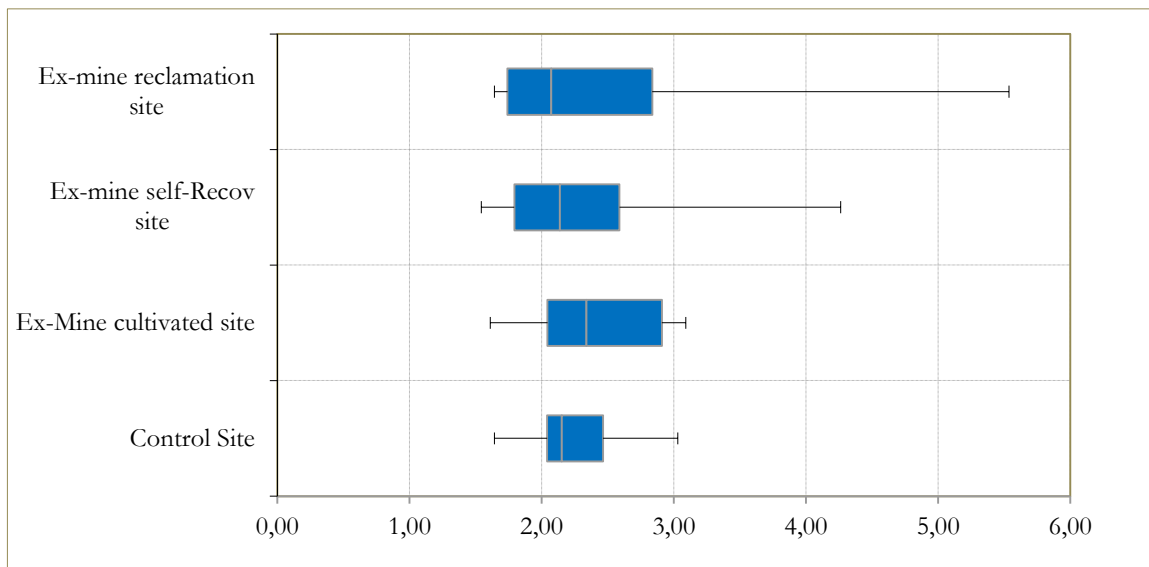
Analysed components include the water holding capacity (WHC), permanent wilting point (PWP), the available water capacity (AWC) and plant available water holding capacity (PAWC) are presented in Table 20 together with soil properties of different sites. Figure 40 also, shows the distribution of the water holding capacity, permanent wilting point and the available water capacity of the different sites.

Figure 39 below summarises the water holding capacity (WHC), the permanent wilt point (PWP) and the available water capacity for plant growth (AWC) expressed in volume percentage (%). The AWC can be converted to Plant available water holding (kL/ha) by apply the formula4.



**Figure 39:** Water holding capacity versus permanent wilting point on experimental sites (%)

WHC and AWC vary from one plot to another. 60 % of Ruhanga series showed the highest WHC  $\geq 20$  %. Also, WHC varies within different plots under different managements, 23.66 % on CS, 25.37 % on CP, and from 26.66 to 27.27 % on RS and SR. The lowest WHC was found on SR with values within 9.67 %. In Gatare mine, the obtained average WHC, PWP and AWC include 20.43 %, 18.07 % and 2.37 % respectively, while in Ruhanga their values are 20.35 %, 18.23% and 2.13 %. Lowest values are recorded in Gatare with 18.89 %, 17.22 % and 1.68 %. Within individual plots of respective mines, characteristics in water retention vary, and high values in AWC are likely found on assisted plots followed by cultivated plots and self-recovering plots.



**Figure 40:** Available water holding capacity (%)

The diagram shows that the ex-mine reclamation and ex-mine cultivated sites have higher values of WHC; followed by the ex-mine self-recovery site, and then the control site respectively. It shows that PAWC is much higher in ex-mine reclamation site followed by ex-mine self-recovering site.

#### 4.2.5.2 Relationship of water holding capacity with other soil variables

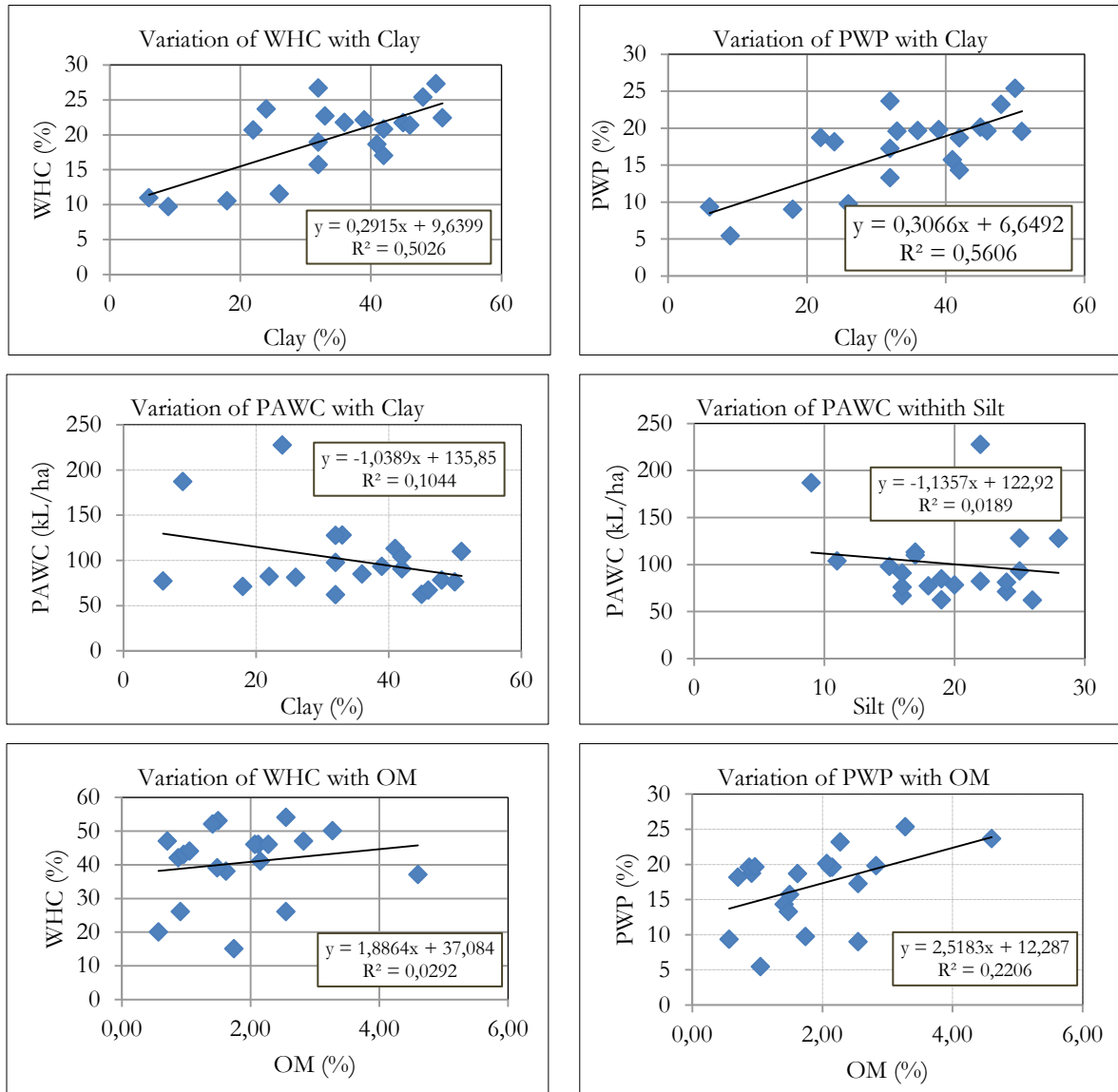
The variation of water holding capacity within the mine sites and on control sites as well were studied to assess whether or not there are similarities or differences.

##### Within the mines

For a better understanding, the water holding characteristics of mines were correlated to soil texture and OM. The clay and OM content are known for their impacts on water retention and availability to plants, which are among the most suitable and useful for this assessment (Saxton et al., 1986). Results of analyses



for the mines are presented graphically below; next to that is for the control site, for understanding whether there is variation in relationship or not.



**Figure 41:** Variation of soil moisture with selected soil variables within the mine sites

As presented graphically in Figure 42 above, there is a positive and significant correlation between clay with WHC and PWP, while silt is negatively and not significantly correlated with PAWC. Although OM is positively correlated with WHC and PWP, the relation is not significant as well. Likewise is the OM, it is negatively and not significantly correlated with the PAWC. The control site shows stronger and positive correlation between WHC, PWP with Clay than they are in mine sites. Furthermore, the correlation of WHC and PWP is significantly and negatively correlated with Silt than they are in mine sites. Both mines

and control sites show poor and negative correlation of PAWC with Clay and OM, but Silt of control site, although poorly fitted, it tends to be positively correlated with PAWC than it is in mines.

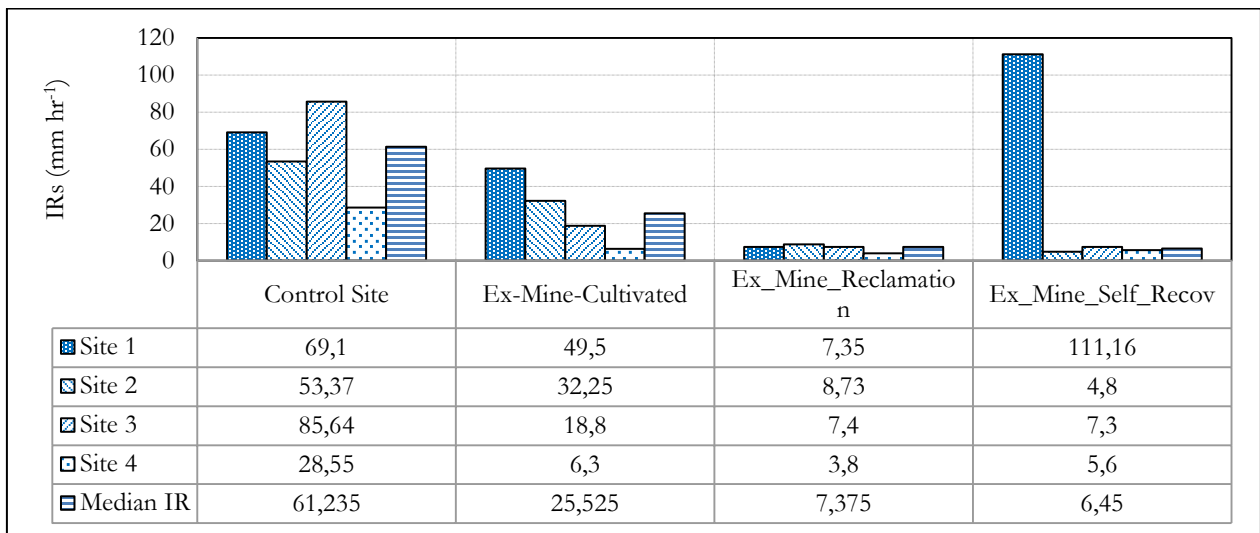
This variation in correlation strength observed between water holding characteristics and related soil variables could denote the variation in disturbance of soil properties mostly in mine sites.

#### 4.2.5.3 Infiltration

Figure 42 below summarises the obtained results of the infiltration rates on various experimental. Infiltration tests run across different sites, 50 % were  $3.8 \text{ mm hr}^{-1}$  and  $18.80 \text{ mm hr}^{-1}$ , slow to moderately slow respectively and 80 % was between  $3.8 \text{ mm hr}^{-1}$  and  $85 \text{ mm hr}^{-1}$ ; slow to moderately rapid respectively. By considering the median values, the control site head the IRs with  $61.3 \text{ mm hr}^{-1}$  followed by ex-mine cultivated sites ( $25.5 \text{ mm hr}^{-1}$ ), ex-mine assisted ( $7.4 \text{ mm hr}^{-1}$ ), and lastly the ex-mine self-recovering site with  $5.6 \text{ mm hr}^{-1}$ . An excessive IR ( $111.16 \text{ mm hr}^{-1}$ ) (rapid) was found on one of Ex-mine self-recovering site. This would be probably caused by the existence of a fissure (mechanical porosity rather than structural porosity), because this is outside of other recorded infiltration values, if we consider the type of soil and the location on which the test was performed.

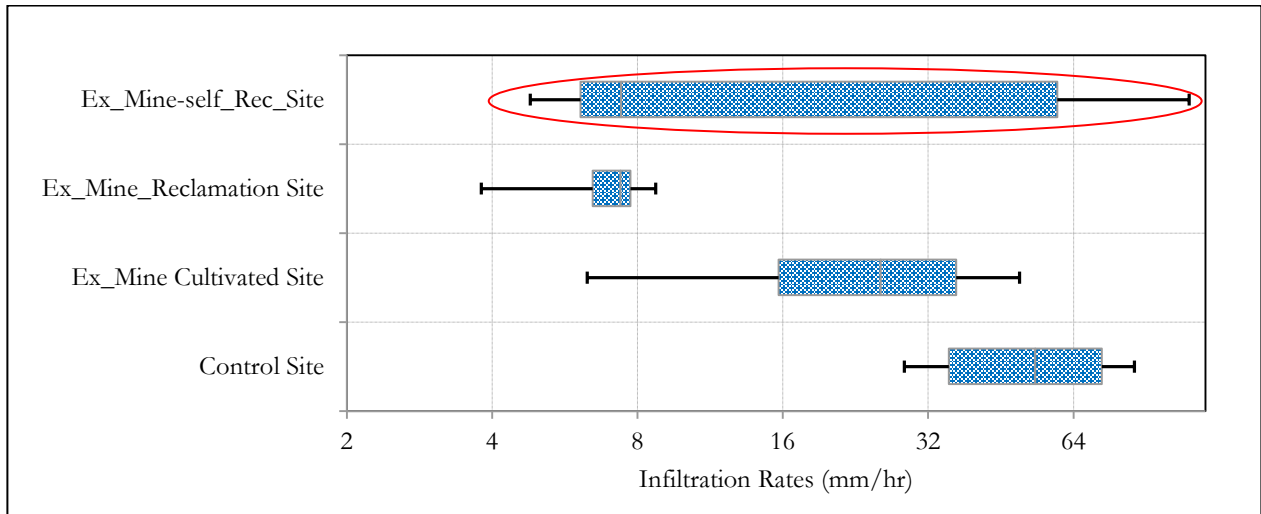
#### 4.2.5.4 Spatial variability in infiltration rates

A spatial variability in water IRs was found different on plots of respective sites as shown in Figure 43. Infiltration rates showed also different shapes of the infiltration curves. This could be ascribed to as resulting from the variability of soil properties that affect the infiltration process.



**Figure 42:** Infiltration rates variation on different sites

On ex-mine self recovering site, infiltration rate was higher on one of four locations than on other sites with similar soil properties. This makes the box and whisker represented on Figure 44 to be more skewed right as. As we have already mentioned, infiltration would be mechanically controlled rather than structure controlled. No relationship was established between clay and silt with IR on ex-mine reclamation site. Infiltration on this site is probably more influenced by organic matter since the site is subjected to restoration experiments. Infiltration on control sites stabilises between 86 and 29  $\text{mmhr}^{-1}$ .



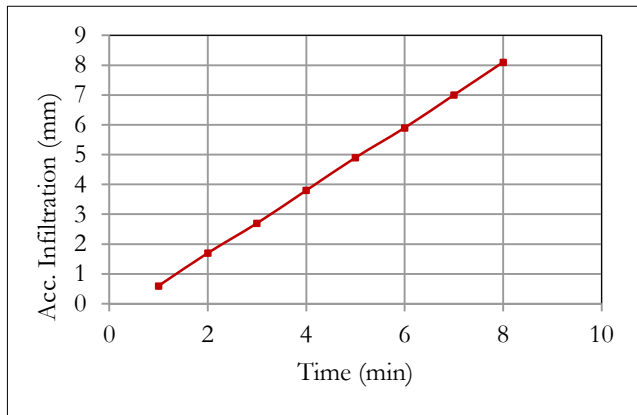
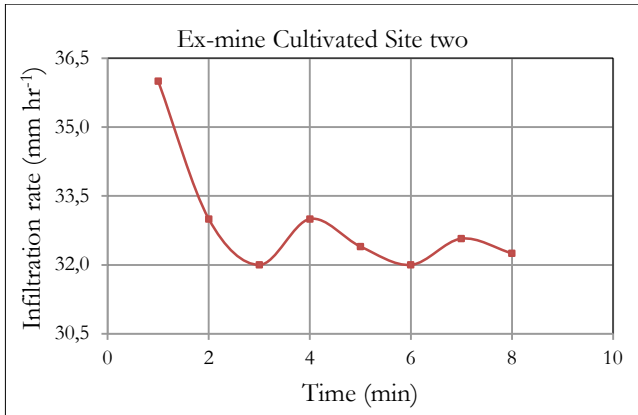
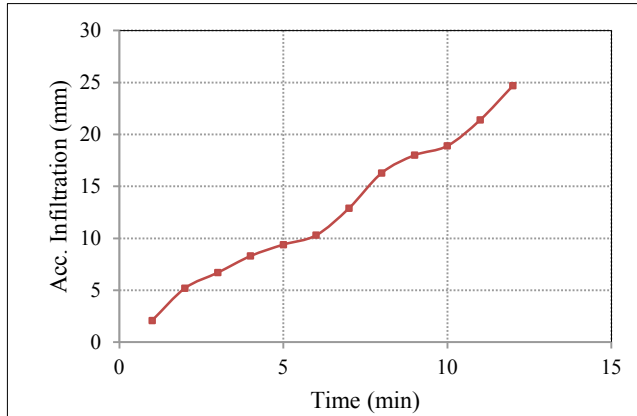
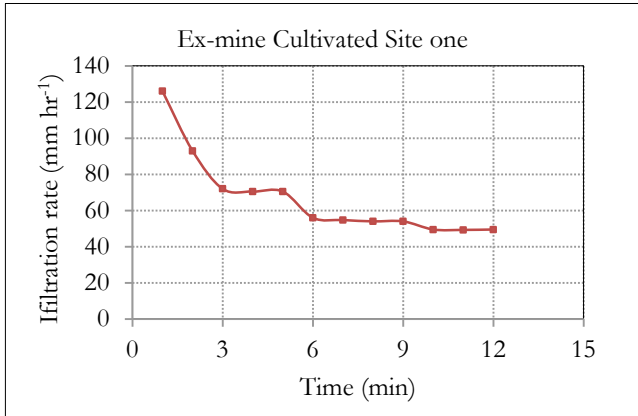
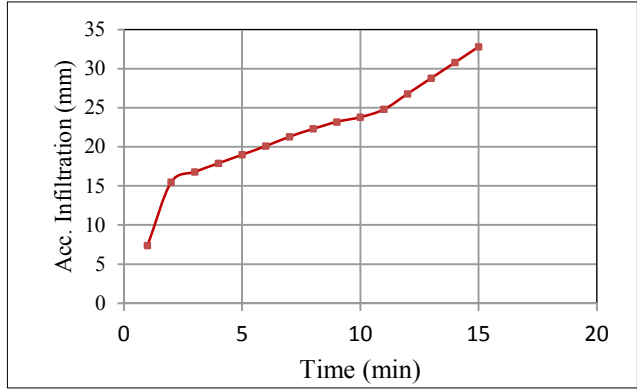
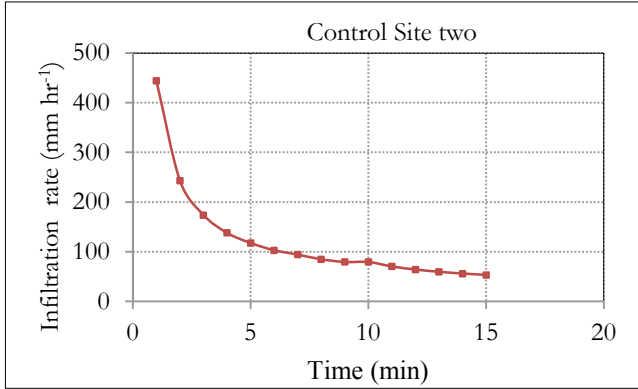
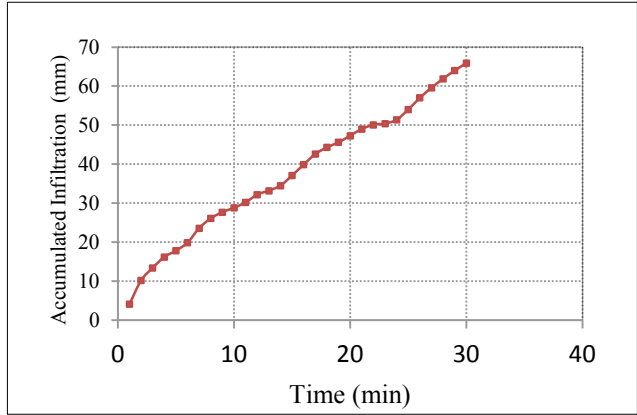
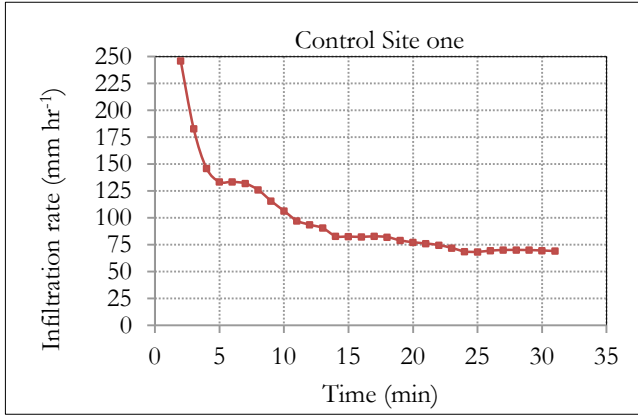
**Figure 43:** Ranges of infiltration rates on different mines plots (n=4 per site)

In the next section, some infiltration curves are presented to assess the infiltration process.

#### 4.2.5.5 Infiltration process on different sites by considering infiltration curve shape

IRs curves showed variability in their shapes, and their steady states occurred at different rates and times on different sites. Figure 45 shows IRs ( $\text{mm hr}^{-1}$ ) and corresponding Accumulated Infiltration (mm). On control sites and ex-mine cultivated sites, IRs curves showed that, initially the rate is high at the beginning of the experiment, and then it decreases regularly at a lower infiltration rate.

As per field tests illustrated on graphs above, high average infiltration rates were observed on control sites and relatively high on ex-mine cultivated sites. On ex-mine reclamation site and self-recovering site, the shape of infiltration curves is distorted. Furthermore, these sites showed lower values of infiltration IR, which often stabilizes between 9 and 4  $\text{mm hr}^{-1}$ .



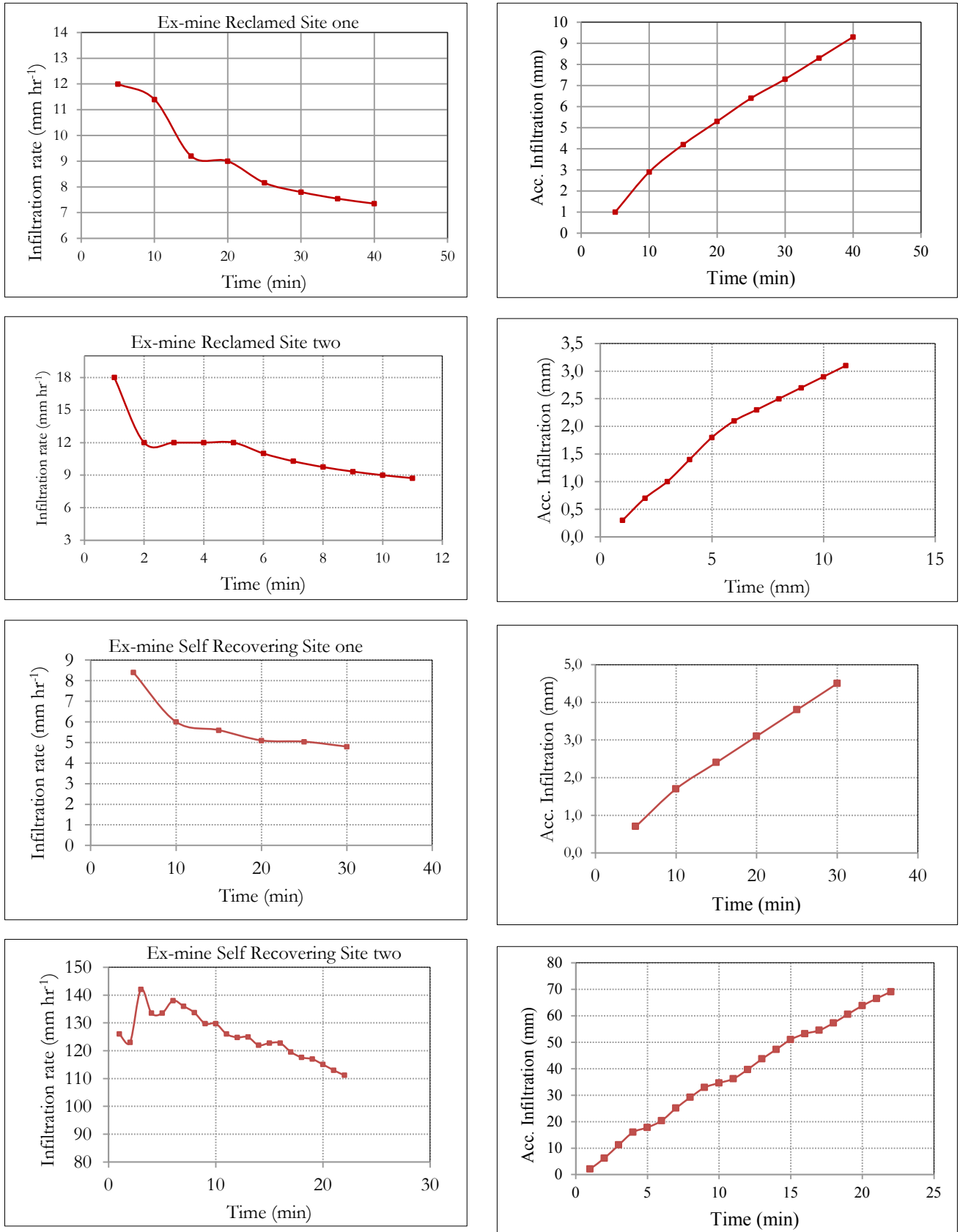


Figure 44: Infiltration rates and accumulated infiltration representing respective experimental sites

#### 4.2.6 Soil consistency analysis

Few samples in specified locations (Table 22) were collected for the purpose of engineering properties test, mainly based on identified lithologies on the field. On the two studied mines, it appears that the pegmatites which most of them are mined are imbedded within schists. On some locations dolerites were also identified but seem to be less extended. In addition to physical and chemical components and all related processes which are mostly privileged in the processes of re-cultivation, engineering tests were not much developed; analyses described in this section intended to highlight some of basic properties of the study area which deserve to be considered for the purpose of stabilizing the slope. The results of engineering properties of soils of the Gatumba mine sites are presented in Table 23. Relationship between soil texture and moisture content and dry bulk density are shown in Figure 46.

**Table 22:** Sampling procedures

Local name	Latitude (decimal)/ Longitude (decimal) Altitude (m)	Designation	Sample depth (cm)	Depth of agricultural soil (cm)	Bedrock	Date of sampling
Gatare	0457355 4786287 <b>1788 m</b>	GA1	60	40	Yellow weathered schist	02/02/2014
	0457319 4786351 <b>1738 m</b>	GA10	60	40	Red weathered Schist	“
	0457259 4786217 <b>1803 m</b>	GA16	60	30	Yellow weathered Schist	“
	0457555 4786065 <b>1753 m</b>	MB1	50-60	30	Pegmatite	“
Ruhanga	0458852 4784878 <b>1656 m</b>	R1	180	40	Dark-grey dolerite	03/02/2014
	0458792 4784693 <b>1698 m</b>	R2	60	40	White weathered Pegmatite	“
	0458767 4784885 1654 m	R3	50-60	40	Yellow weathered schist	“

#### 4.2.6.1 Particle size distribution

Analysed soil samples derived from different parent materials, at a depth of B horizon. The major groups include schist (found on extensive part of the study area), pegmatite and dolerite, with probably different levels of weathering due to the development of thick laterites in some regolith masses. No sample related to transport and deposition was tested. Soils developed on meta-sediments and basalt rocks have a high fine fraction, with the highest fraction 72 % by weight of fines associate with schist in Gatatare. These are deeply weathered red soils, mostly ferruginous and clayey which are the products of weathering in tropical latitudes (Anon, 1979). Identified dolerite presents soil fine amounting relatively lower 55 % in Ruhanga; whereas soils developed on pegmatites in Ruhanga possess a high proportion of sand (73. 2% and 59 %) by weight. This later situation could be associated with the abundant content of micaschist with large crystals of muscovite (Biryabarema & Nkanika, 2001).

#### 4.2.6.2 Atterberg Limits

Atterberg Limits tests are used by engineers for classifying soils and for predicting stability of building foundations (Mapfumo & Chanasyk, 2008).

**Table 23:** Measured engineering properties of Gatumba soils

S/N	Test	Engineering Properties of Gatumba soils							
I.	Sample no	GA1	GA10	GA16	MB1	R1	R2	R3	
	Z (Depth in m)	0.60	0.60	0.60	0.55	1.80	0.80	0.55	
1	Dry bulk density (g cm <sup>-3</sup> )	1.523	1.496	1.514	1.684	1.546	1.496	1.487	
2	Natural Moisture Content MC %	18.86	18.27	18.66	9.88	24.47	21.18	21.31	
3	Atterberg limits %								
	Liquid Limit LL	44	44	26	40	51	43	36	
	Plastic Limit PL	22	22	20	24	22	18	18	
	Plasticity Index PI	22	22	6	16	29	25	18	
	Linear Shrinkage LS	8.7	10	8.7	6.7	8	8.7	6.7	
	Percentage Swell considering Z (Hicks, 2000)	1.0	1.0	1.0	1.0	0.7	1.0	1.0	
	Shrink-Swell potential	Low	Low	Low	Low	Low	Low	Low	
4	Class of Soil	<b>OL</b>	<b>CL</b>	<b>ML</b>	<b>CL</b>	<b>CH</b>	<b>OL</b>	<b>CL</b>	
6	Sieve Analysis (Sieve Size )	Percentage Passing %							
	14.00mm	100	100	100	100	100	100	100	
	10.00mm	100	100	100	100	100	100	100	
	4.75mm	100	100	99.2	91.6	96.6	96.2	100	
	2.36mm	99	99.4	93.8	76.2	94.4	94.6	98.6	
	1.18mm	98.2	98.8	59.4	64.4	92.2	93.2	96.8	
	600 µm	97.4	98.2	87.8	55.8	91	90	96	
	425 µm	96.6	97.8	87	50	90.2	87.2	94.2	
	300 µm	95.2	97	86	44.2	89	83.6	88.8	
	150 µm	84.6	91	80.6	33.8	78.6	72.8	58.4	
	075 µm	70.2	68.6	67	26.8	64.6	57.6	41	

Four soil types encountered include Inorganic clay of low to medium plasticity (CL); Inorganic clay of high plasticity (on or above A-line) (CH); Organic silt and organic silt-clay of low plasticity (OL); and Inorganic silts and very fine sands with slight plasticity (ML).

These properties are essential to estimate soil swelling potential and expansive rating of soils known as Atterberg Limits, which are defined as water contents of fine grained soils at different states of consistency (Brady & Weil, 2014). These are in relation to a number of phenomena, including the elastic rebound of soil particles, attraction of clay mineral for water, electrical repulsion of clay particles and their adsorbed cations from each other, and the expansion of air trapped in the voids (Hicks, 2007). Liquid Limit (LL) values range between 26 and 51% all present low to medium shrinkage-swell potential. Laboratory tests have shown generally low and intermediate Plasticity Index (PI) ranging between 18 and 29 %, with only one soil sample that has 6 % PI. Commonly, a high linear shrinkage LS indicates a large potential shrinkage of the soil mass on drying, and places limitations on the use of the soil as foundations for small Buildings (Hazelton & Murphy, 2007).

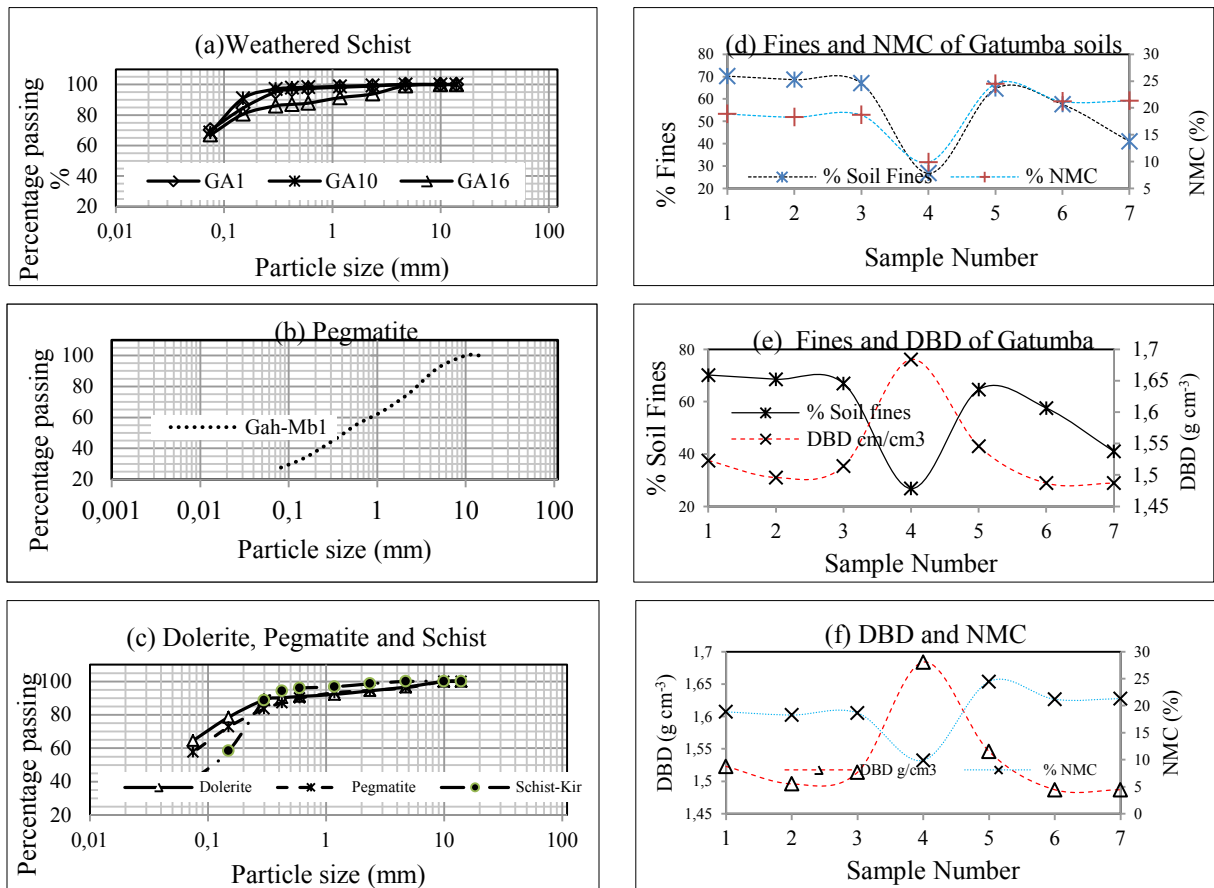
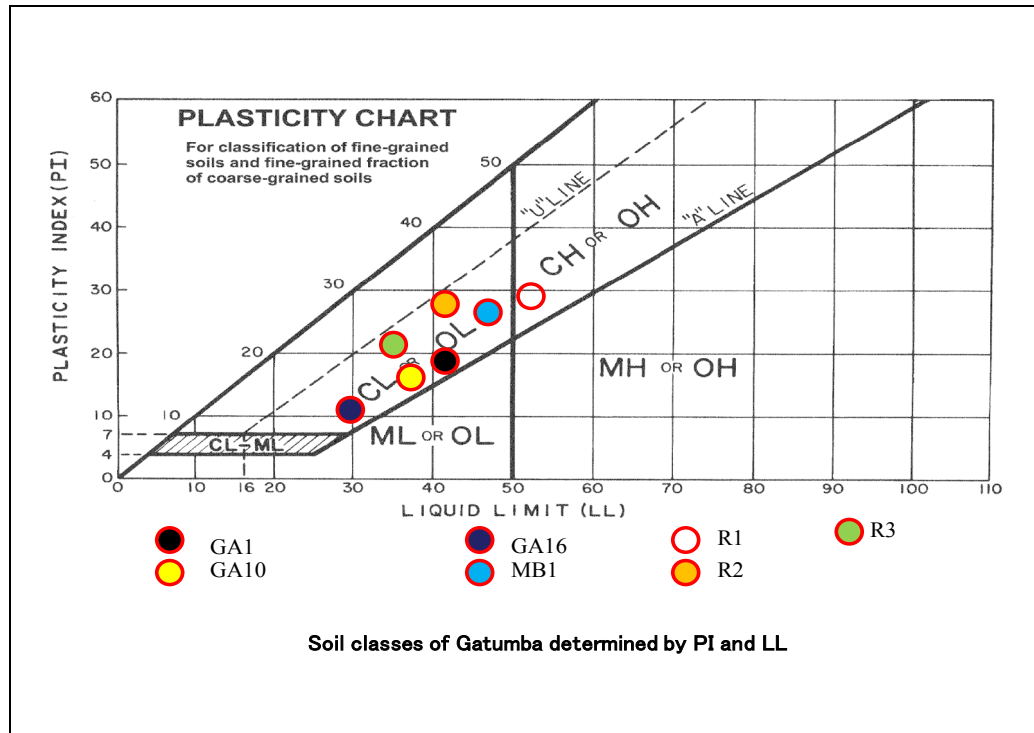


Figure 45: Grading curves of fine developed on different parent materials



(a-c) the distribution of soil fine fraction, in relation with (d) natural moisture content “NMC”; and (e) dry bulk density “DBD”, and relation with DBD and NMC (d-f).

A plot of plasticity indices (PI) versus the Liquid Limit (LL) in a plasticity index chart was prepared and presented in Figure 47. In this study no sample was taken from alluvial plain. Among them are alluvial sand and gravely sand, and laterite formed on quartzite.



**Figure 46:** Atterberg Limits of soils developed on major types of parent materials

### 4.3 Modelling soil erosion

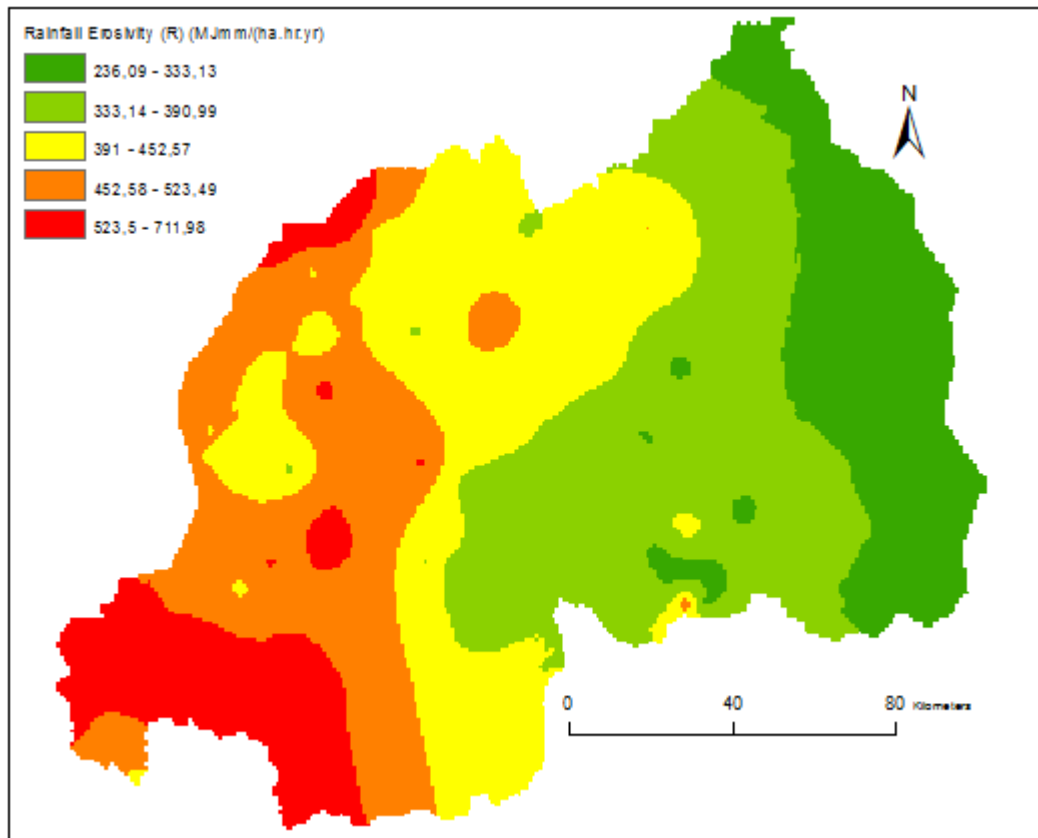
RUSLE is a straightforward and empirically based model that has the ability to predict long term average annual rate of soil erosion on slopes using data on rainfall pattern, soil type, topography, crop system and management practices (Prasannakumar et al., 2012). Based on available rainfall data, erosivity country wide was performed prior to assessing soil erosion risk in the study area. The former exercise intended to get the erosivity coefficient for different regions of Rwanda. The later exercises aimed at assessing soil erosion risk in the studied watershed, and constituting catchments. In order to quantify, evaluate and generate maps of soil erosion risk and severity of the study area, various maps extracted for R, K, LS, C and P

factors of the RUSLE model were multiplied within the raster calculator option of the Arc GIS spatial analyst to get the final output.

### 4.3.1 Rainfall erosivity - R Factor

#### 4.3.1.1 Rainfall erosivity and erosivity coefficient

Rainfall characterizing Rwanda and specifically the western highlands might be regarded as one of major triggering natural factors of soil erosion which is much more aggravated by intensive land use. Rainfall erosivity estimated values for rainfall stations country wide enabled to produce, by the mean of kriging interpolation the isoerosivity map of Rwanda (Figure 47) and erosivity coefficients for individual regions. Countrywide and regional maps of mean erosivity are presented on Figures 47 - 49. To come up with both rainfall erosivity and coefficient maps, data were cross validated. The benefit of this process is that cross validation uses all of the data to estimate the trend (Kouli et al., 2008). Then it omits each data location, one at a time, and predicts the associated data value. The predicted and actual values at the location of the omitted point are compared.



**Figure 47:** Rainfall erosivity countrywide

For all points, cross-validation compares the measured and predicted values. For the standardized error estimation, the measured values are subtracted from the predicted values and then divided by the estimated standard errors. Generally, the best model is the one that has the mean nearest to zero and the smallest root-mean-squared prediction error. If the prediction errors are unbiased, the mean prediction error should be near zero, but can sensibly change depending on the scale of the data.

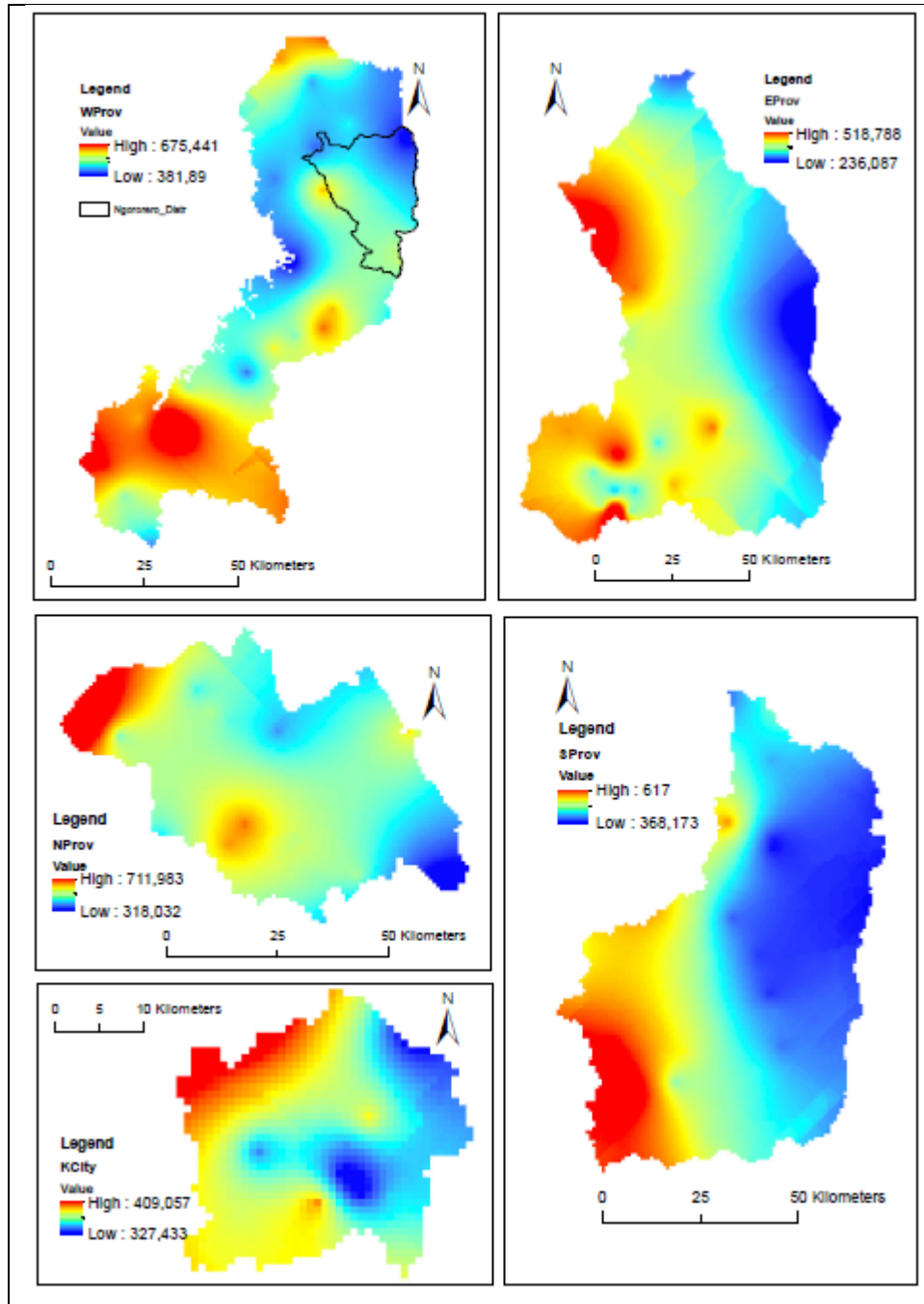
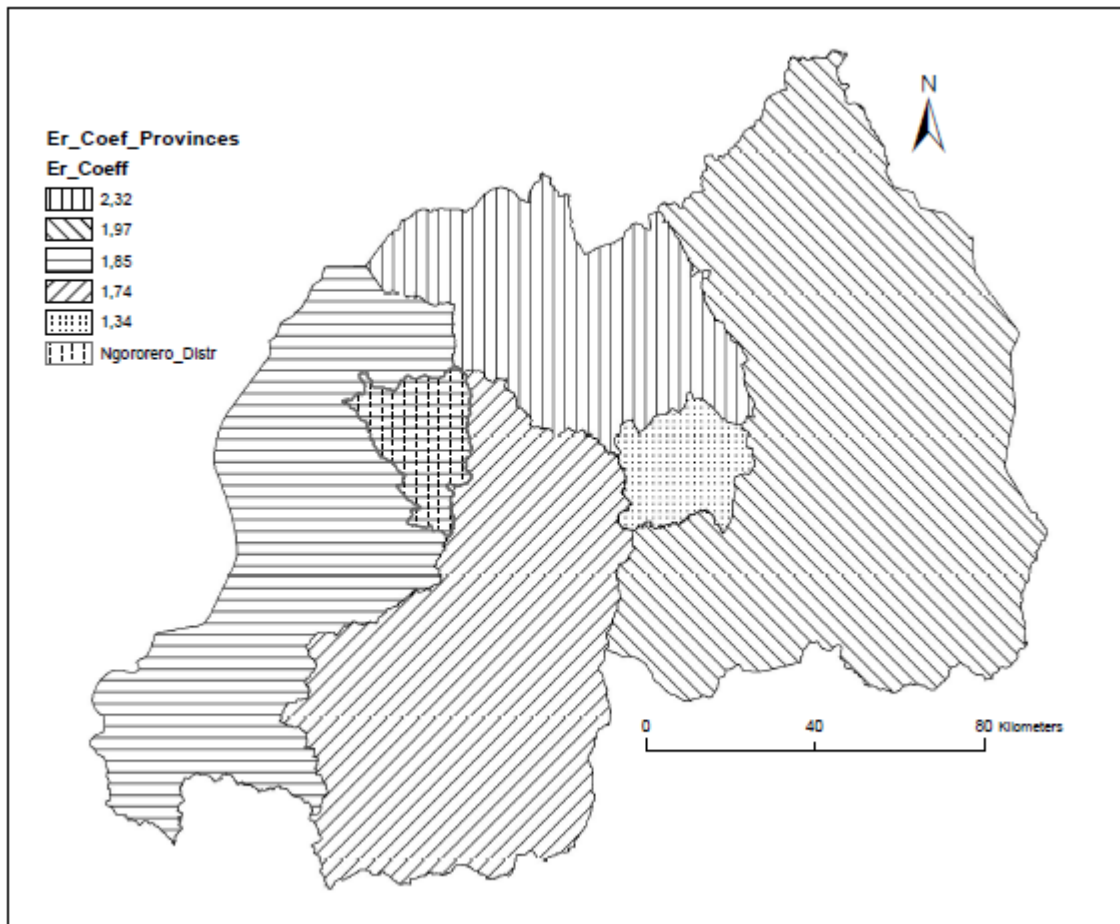


Figure 48: Rainfall erosivity per Province

Differences of mean annual erosivity values may reflect the potential risk of erosion by rainsplash, overland flow and rills. A best fit regression equation was used to predict erosivity values from available measured rainfall. Later we have extracted R factor from regional one to find a local R factor for the study area. The R factor was calculated for regions countrywide and the study area as well using equation 17, and the erosivity coefficient which is the coefficient of maximum and minimum ranges of R factor.



**Figure 49:** R Factor coefficient per region

R factor for individual regions is given in (Figure 49). From the mean values R factor was classified in high, medium and low erosivity classes. The western Province (where the study area is located) followed by the Northern Province area the most exposed to high erosivity ( $528.665$  and  $515.07 \text{ MJ mm ha}^{-1} \text{ hr}^{-1} \text{ yr}^{-1}$  respectively), while the Southern Province and the Eastern Province present a medium class with  $492.586$  and  $469.02 \text{ MJ mm ha}^{-1} \text{ hr}^{-1} \text{ yr}^{-1}$  respectively. Kigali region has the lowest R factor ( $368.249$ ) if we compare it with that of other regions. The erosivity coefficient of respective region (Figure 50) accounts for spatial variability in R factor within individual regions. The bigger the coefficient of the region is, the more the R

factor is distributed within the region. The size of the region has therefore an impact on the coefficient, whereas on small area the erosivity coefficient becomes smaller. The R factor countrywide increases progressively westwards and northwards, and shows a positive correlation with the rain fall rise and topography elevation.

#### **4.3.1.2 Rainfall Erosivity - R Factor**

In order to obtain R factor for the local study area, a statistical weighted moving average technique was applied to get rainfall and interpolation methods in ArcGIS as described in the methodology. The Inverse Distance Weighted (IDW) interpolation methods in ArcGIS is one of procedures used to predict the values of cells at location that lack samples points. R-factor was calculated using equation 17. In the study area R factor is in the range of 266 and 573 MJ mm ha<sup>-1</sup> hr<sup>-1</sup> yr<sup>-1</sup>. R-factor distribution increases with the topographic elevation. The northeast topographic lows present lower values whereas elevated topography is much subjected to high R factor due to increasing rainfall average. When compared to the R factor values obtained in Malaysia (Teh, et al., 2014), which were of very high erosivity ( $699 < R < 951$  MJ mmha<sup>-1</sup> hr<sup>-1</sup> yr<sup>-1</sup>), the R values (266 -573 MJ mm ha<sup>-1</sup> hr<sup>-1</sup> yr<sup>-1</sup>) showed that, climatologically the Gatumba catchment has intermediate to high erosion potential, since erosivity does not exceed 600MJ mm. ha<sup>-1</sup> hr<sup>-1</sup> yr<sup>-1</sup>.

However, in spite of showing intermediate to high erosivity values, which could not cause high risk of erosion, studies pointed out that erosivity risk increase when the occurrence of unusual storm conditions occur (Bayramin et al., 2006). Their argument was based on the frequency analysis performed with the modified Fournier index (MFI). Region experiencing low rainfall can record highest erosivity potentials. In Europe for instance, the highest rainfall erosivity risk is identified in areas with low annual mean precipitation. Highly erosive rainfall hits long-period dry soils which usually causes great damage and is connected to a very high flood risk (Diodato et al., 2011). Therefore, knowledge of seasonal and spatial distribution of unusual storm event conditions with high erosivity potential is of immense importance for soil erosion research and management.

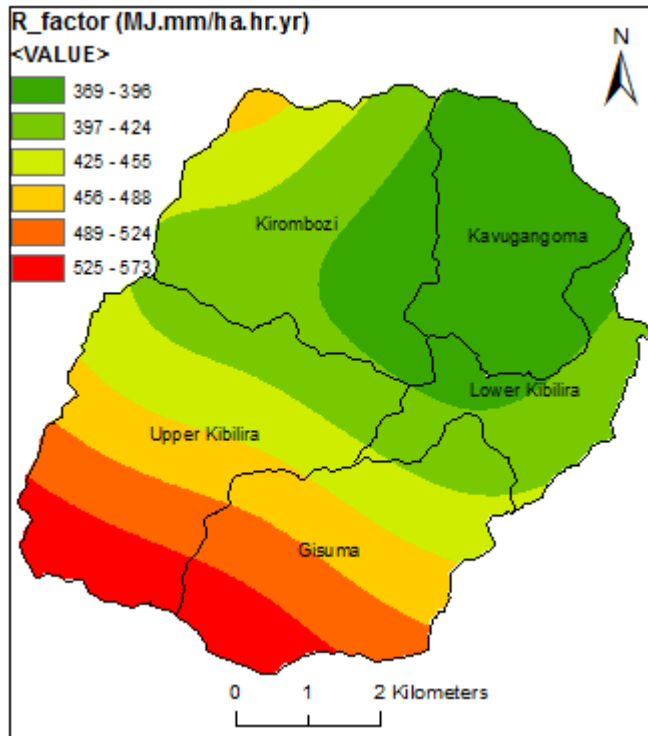


Figure 50: R factor Map of Gatumba watershed

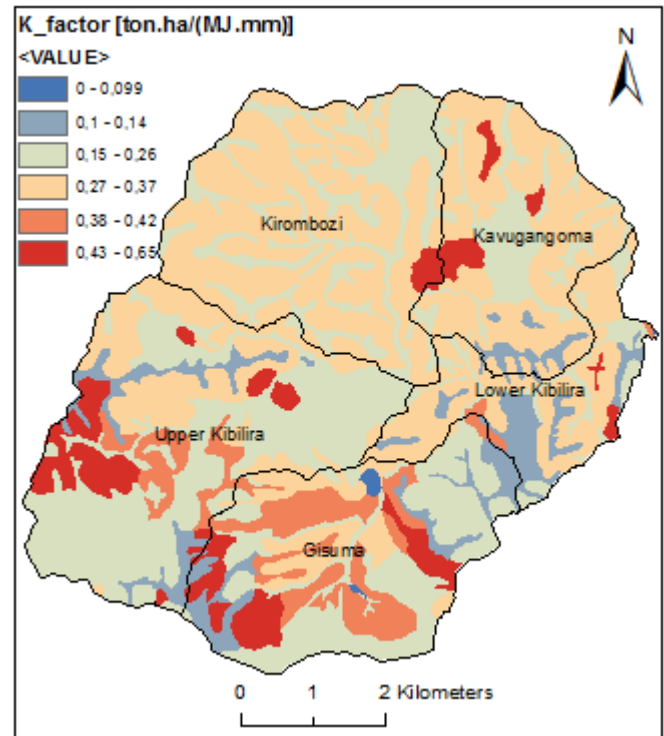


Figure 51: K factor Map of Gatumba watershed

#### 4.3.2 Soil Erodibility - K Factor

K factor maps were produced based on the soil map and soil erodibility, which depends on soil texture and OM content (Table 10-11). Three scenarios were compared depending on the OM content indexes. For  $OM > 2\%$  K factor ranges from 0 to 0,55; with  $2\%$  OM K factor comprises between 0 and 0,65 and less  $0,5\%$  OM has K factor index from 0 to 0,75 (Figures 51-53). Thus soil erodibility factor varies from  $0.01$  to  $0.75 \text{ t ha}^{-1}/(\text{MJ mm})$ , with mean class value of  $0.55\text{-}0.66 \text{ t ha}^{-1}/(\text{MJ mm})$ . Erodibility indexes assigned to different types of soils showed that the most easily erodible soils are mines followed by silty soils, and the less erodible soil particles are aggregated soils with relatively high amount of organic matter.

#### 4.3.3 Topographic length and steepness – LS Factor

DEM was firstly converted to slope map in degree and flow direction map. Afterwards, the flow direction map was used to create maps of flow length and flow accumulation. Flow accumulation was used to estimate the contribution of upstream cells in a DEM to the downstream cells, based on drainage area. The slope length (L) and slope steepness (S) are combined in a single topographic slope length and gradient index, LS factor. The processing in GIS was performed using equations (19-26) The Figure 52 presents the spatial distribution of LS factor in the watershed. Generally, the LS factor reaches high values due to the steepness and length of slope, nearly 15.



#### 4.3.4 Support practice – P Factor

P factor (Figure 53 and Figure 55) was generated through the reclassification of slope and conservation indexes corresponding to support practices given in chapter 3 (Table 12) Because on the combination of techniques applied to mitigate erosion within the study area, we used mean of indices corresponding to different support practices summarized in Table 24 to find the average of actual soil erosion rate.

#### 4.3.5 Land cover – C Factor

Land cover map of the area was used as the basis to determine the C-factor (Figure 56). This approach was used by several researchers on areas whose natural vegetation was totally replaced by anthropogenic one, and where data base for individual factors of the RUSLE is not available. To avoid the overestimation of C factor which for such regions is estimated to 1 index value, to each crop was assigned a corresponding index obtained from the literature (Morgan, 2005). Based on this approach, the obtained C Factor was found to range from 0.2 to 0.5.

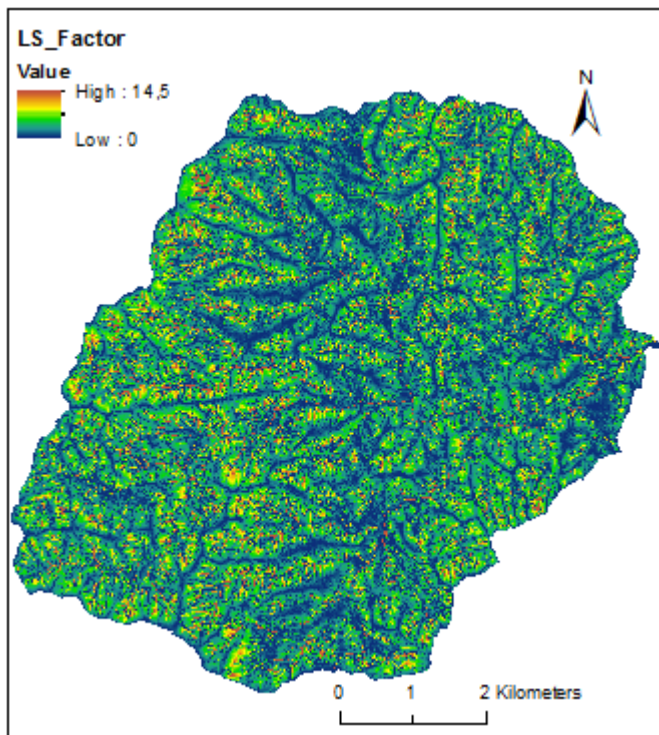


Figure 52: LS factor Map

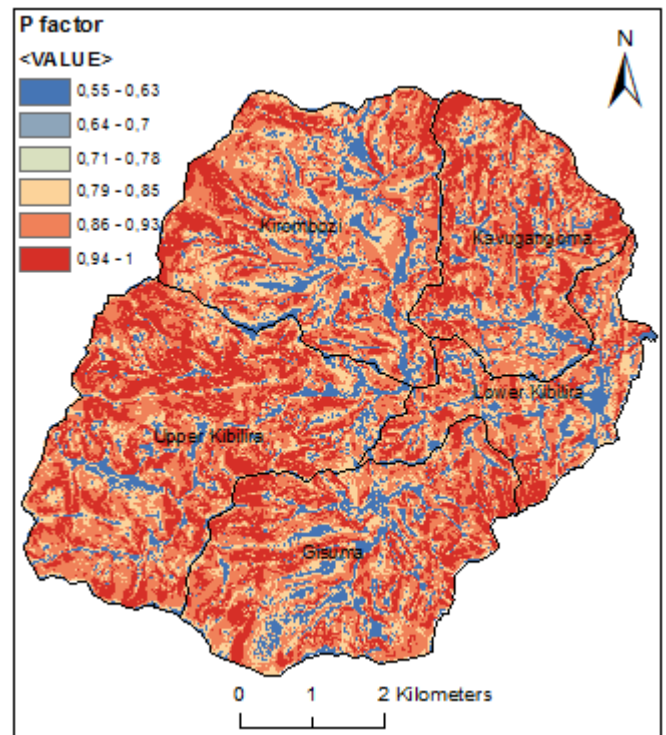


Figure 53: P factor Map with Strip cropping

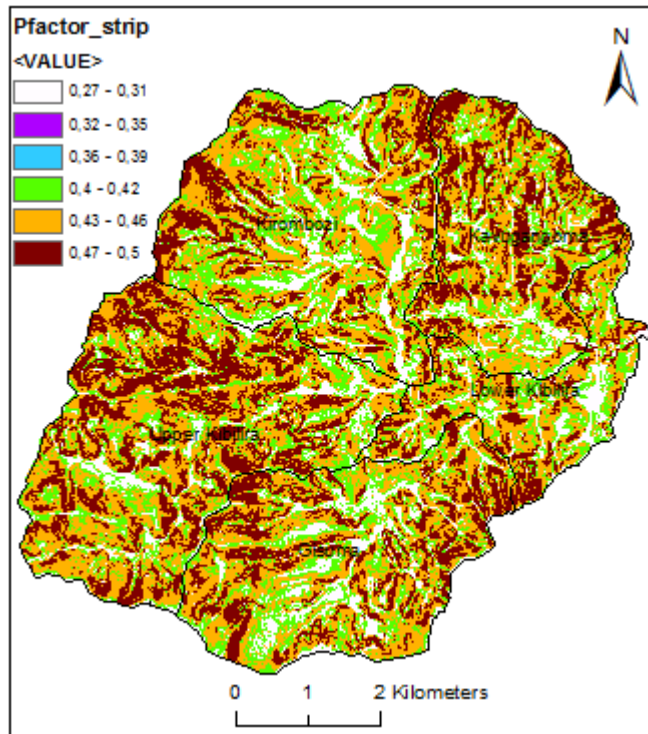


Figure 54: P factor Map with strip practice

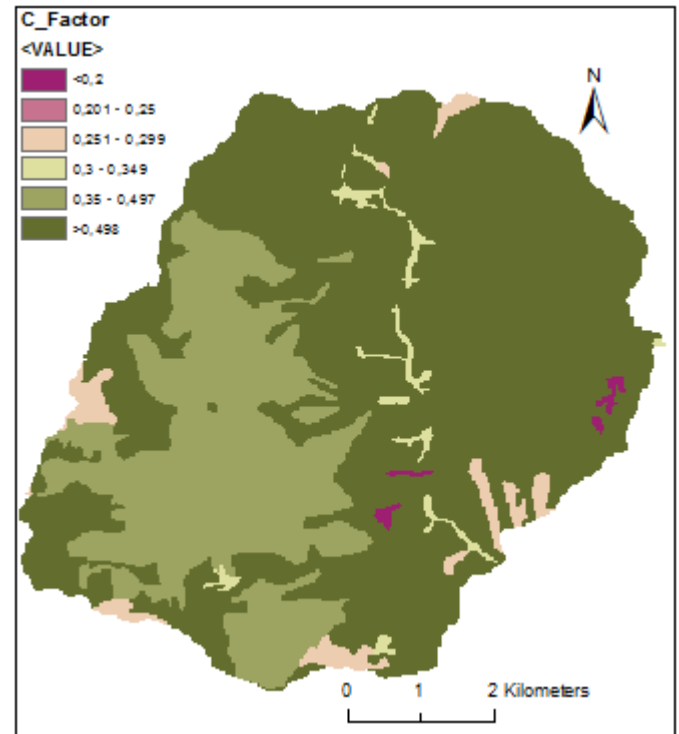


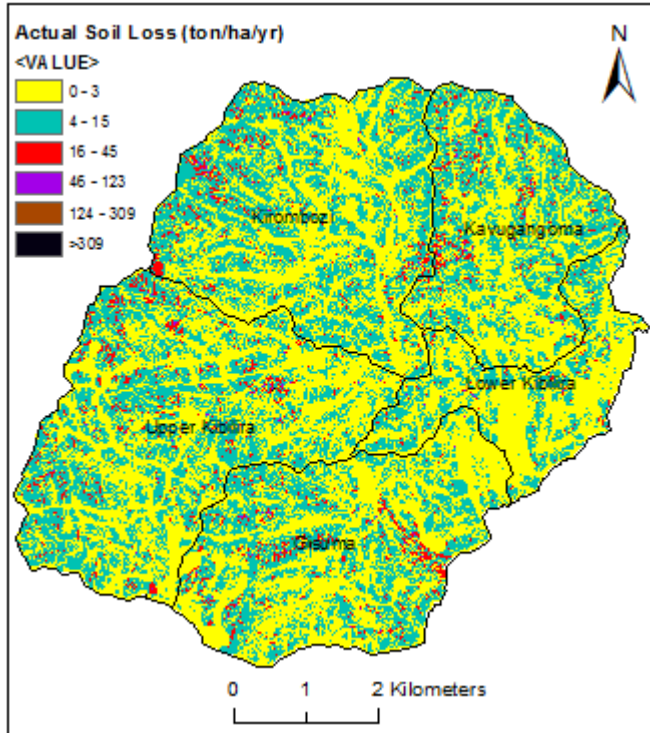
Figure 55: C factor distribution

#### 4.4 Soil loss prediction in the study area

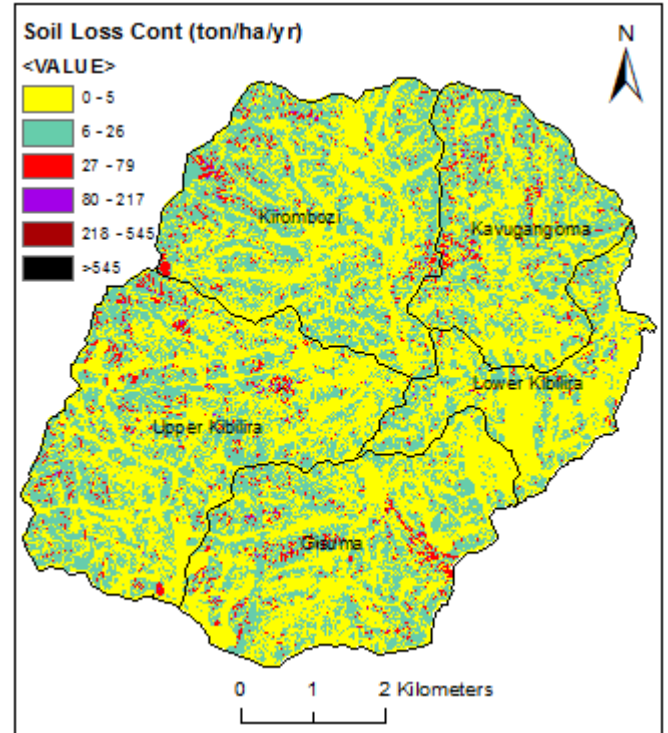
From what has been described so far it follows that the impact of geomorphic processes on land in hilly zones with a relatively dense population and intense land use not only has the potential of depleting soil productive capacity but also making it vulnerable at different degrees of risk for their degradation and erosion (Grecu, 2002). The localization of risk factors, that is of geomorphic processes and morphodynamic potential is a preliminary stage in drawing up a map of risk-prone lands (Grecu, 2002). Geomorphic factors and processes that control the delivery, transport and storage of sediment are not only scale-dependant (Osterkamp & Toy, 1995), but also in mined sites landscape can significantly change by order of magnitude depending on the intensity of mining and strategies to alleviate their impacts. Soil loss is therefore connected to geomorphic processes because mining activities impacts on properties of soil making it more vulnerable to erosive agents. For instance, analyses have shown that soils of mine sites have lower OM content than control sites. Furthermore, different erodibility indexes assigned to K factor showed that soil erosion potential increases with decreasing OM content. This applies to cropping management system as well. In other words, geomorphic processes in mine sites are likely to accelerate with alteration of soil properties or disturbance of the ground.



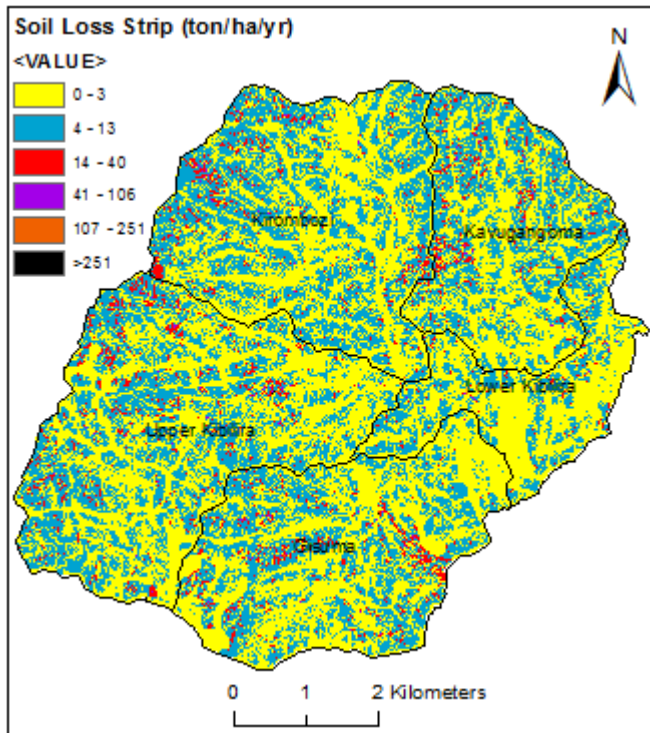
In view of this, the best method commonly used is the superposition of factors controlling soil erosion in order to outline areas of high soil erosion risk. After completing data input procedure and preparation of R, K, LS, P and C maps as raster data layers, they have been multiplied in the GIS 10 using equation (11) to provide erosion risk maps which show spatial distribution of soil loss potential in the study area. Average of soil erosion rates were calculated based on slope classes. Actual soil loss Figure 56 was averaged from different support practices and K values (Table 10). Furthermore, different scenarios were studied based on factors which can be modified by human activities (P factor and K factor). This showed that soil erosion rates change if geo-environmental scenarios are changed (Figures 57-59). Furthermore, the classification of soil erosion rates in numerical severity ranges suggested in different literatures is not uniform, because it depends mainly on the flatness or the steepness of the terrain, and types of management implemented for that particular terrain. For instance, Prasannakumar et al.(2012) classified the severity of soil erosion in null ( $0 \text{ t ha}^{-1} \text{ yr}^{-1}$ ), Low ( $0-1.5 \text{ t ha}^{-1} \text{ yr}^{-1}$ ), Moderate ( $1.5-5 \text{ t ha}^{-1} \text{ yr}^{-1}$ ), and High ( $>5 \text{ t ha}^{-1} \text{ yr}^{-1}$ ). Farhan et al. (2013) and Drzewiecket al. (2013) classification summarized in table 23 considers terrain with steep slope. Soil erosion rate was classified as Low if it comprised between 0 and  $1 \text{ t ha}^{-1} \text{ yr}^{-1}$ , Slight ( $1 \text{ and } 3 \text{ t ha}^{-1} \text{ yr}^{-1}$ ), Moderate (3-5), High ( $5.01 - 10 \text{ t ha}^{-1} \text{ yr}^{-1}$ ) and Severe ( $>10 \text{ t ha}^{-1} \text{ yr}^{-1}$ )(Demirci & Karaburun, 2012). Results show that values of actual soil erosion rate approximately equal those of strip support practice scenario (Figures 57-60 and Tables 27-29).



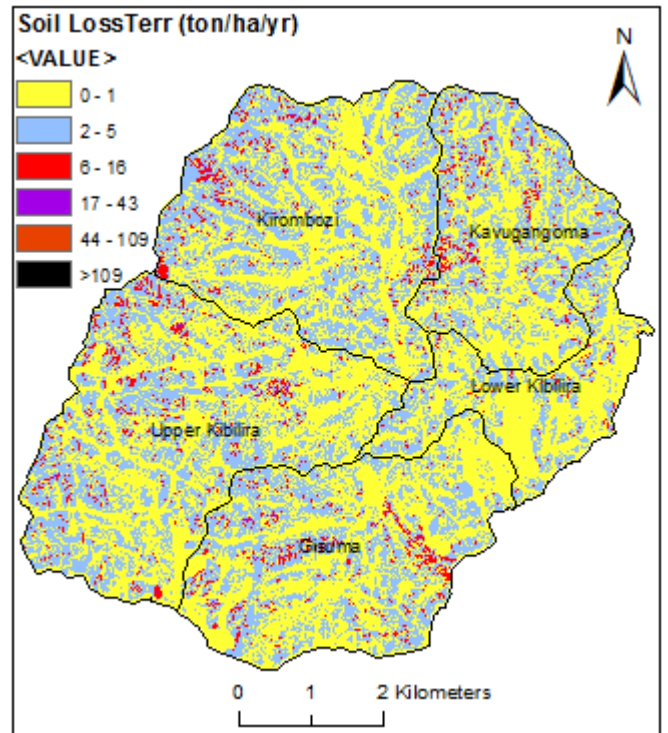
**Figure 56:** Actual spatial distribution of soil loss ( $t\ ha^{-1}\ yr^{-1}$ )



**Figure 57:** Spatial distribution of soil loss with contour support practice ( $t\ ha^{-1}\ yr^{-1}$ )



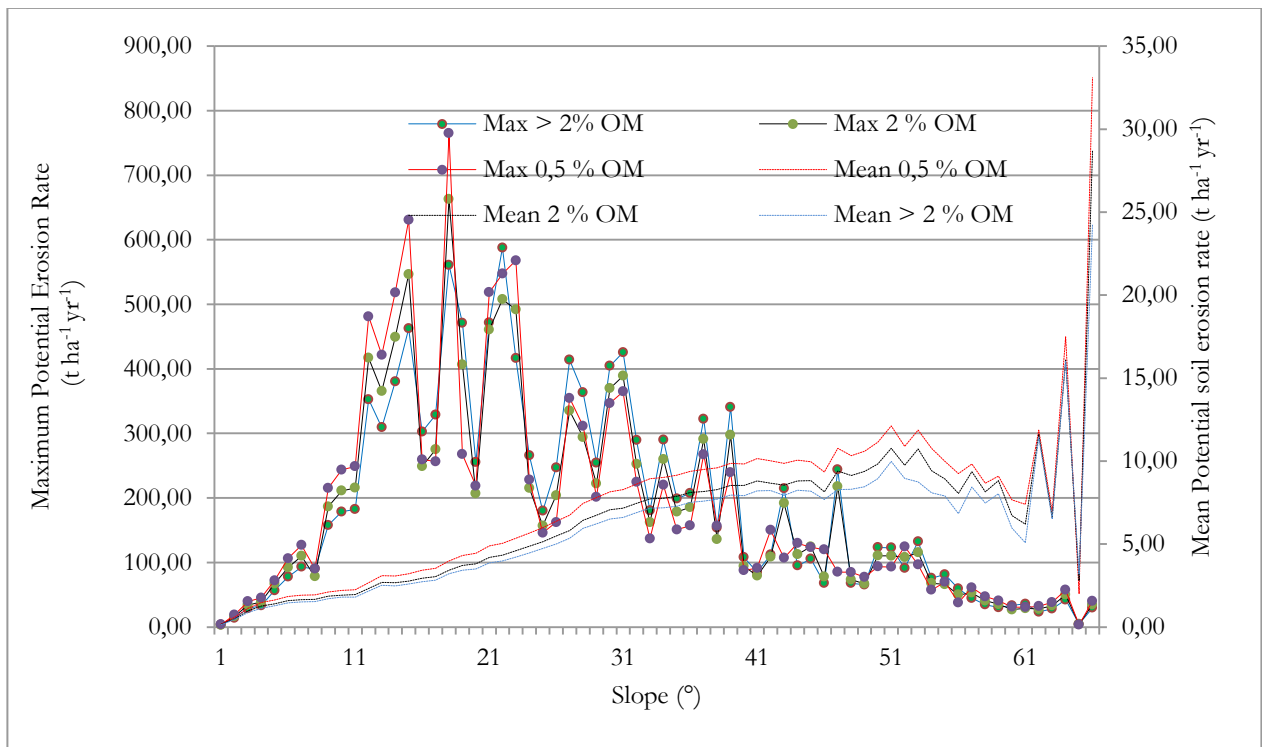
**Figure 58:** Soil erosion potential with strip support practice ( $t\ ha^{-1}\ yr^{-1}$ )



**Figure 59:** Soil erosion potential with terrace support practice ( $t\ ha^{-1}\ yr^{-1}$ )

**Table 24:** Erosion classes and soil degradation adapted from Fahran et al. (2013) and Drzewiecki et al. (2014)

Erosion class	Erosion description	class	Numerical range (t ha <sup>-1</sup> yr <sup>-1</sup> )	Soil degradation
1	Minimal		0-5	Small surface soil loss
2	Low erosion		5-15	Visible wash-off of humus horizon and deterioration of soil properties full regeneration of soil not always possible through conventional tillage
3	Moderate erosion		15-25	May lead to a total reduction of humus horizon and the development of soils with typologically unformed profiles; terrain dismemberment starts, considerable debris flow into surfaces waters
4	Severe		25-50	Can cause total destruction of the soil profile, including parent rock; formation of badlands and deformation of hydrology
5	Extreme		>50	Can result in a permanent degradation of the ecosystem



**Figure 60:** Actual soil erosion rate (t ha<sup>-1</sup> yr<sup>-1</sup>)

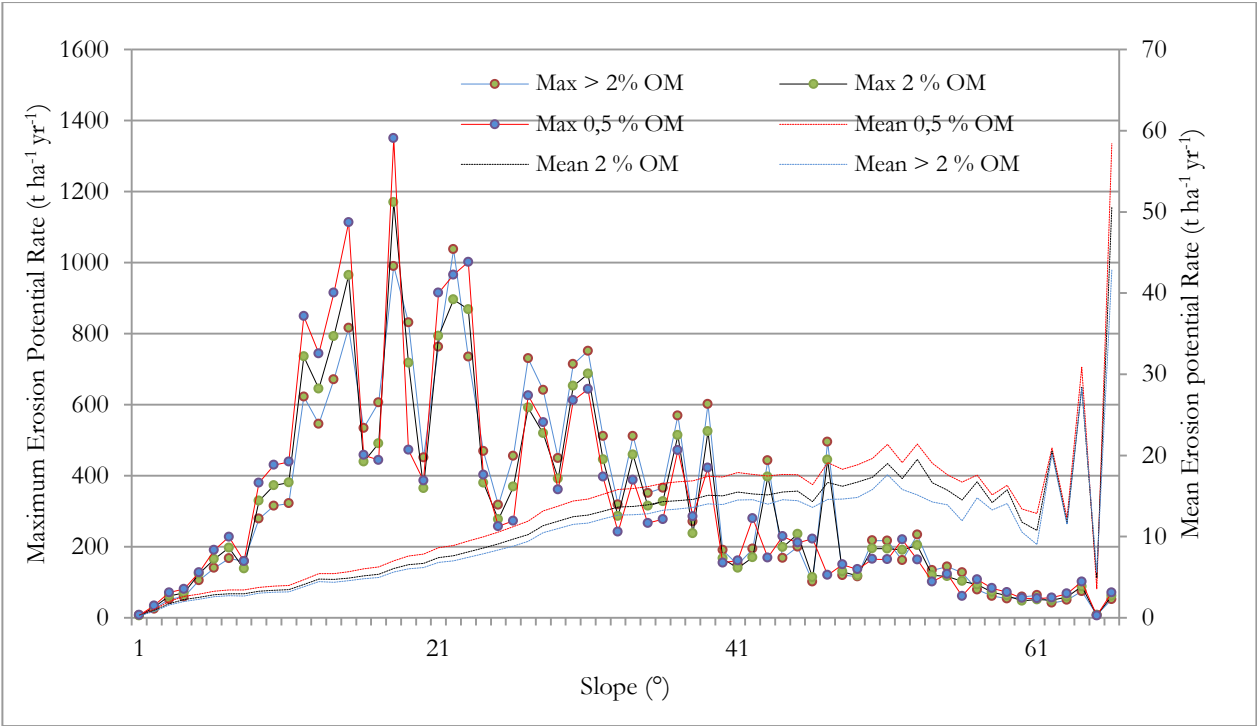


Figure 61: Soil erosion potential rate following OM with contouring support practice

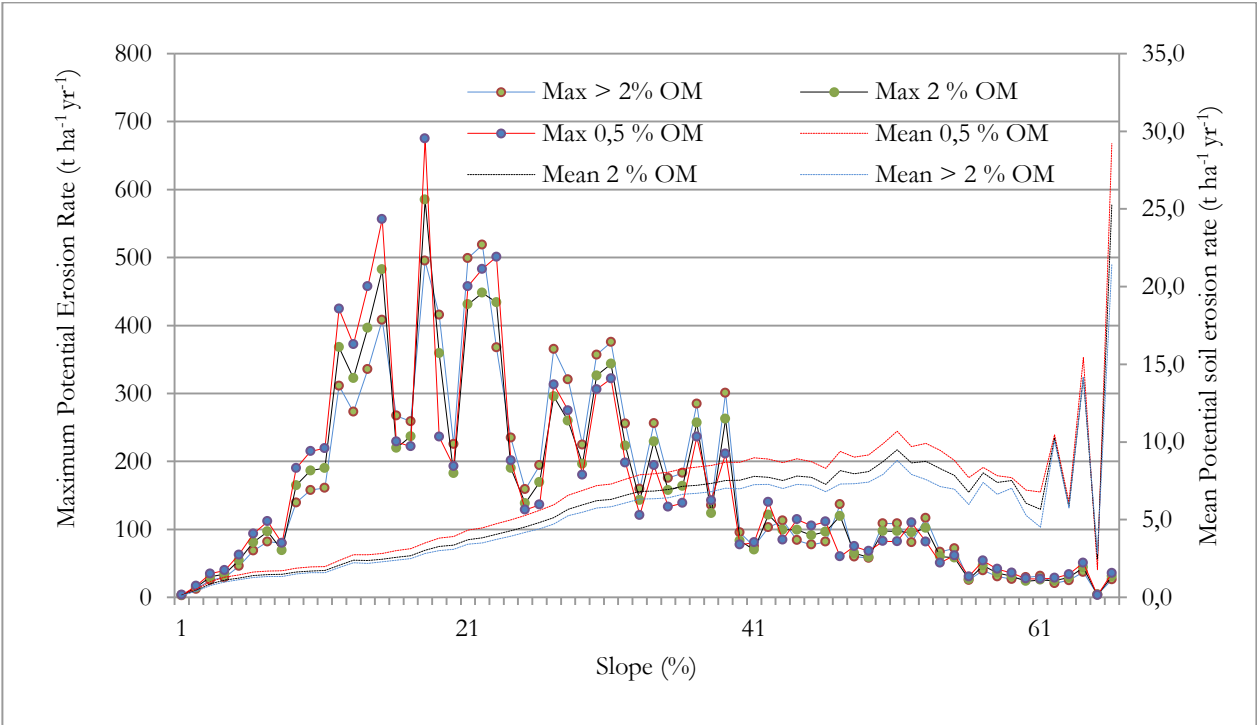
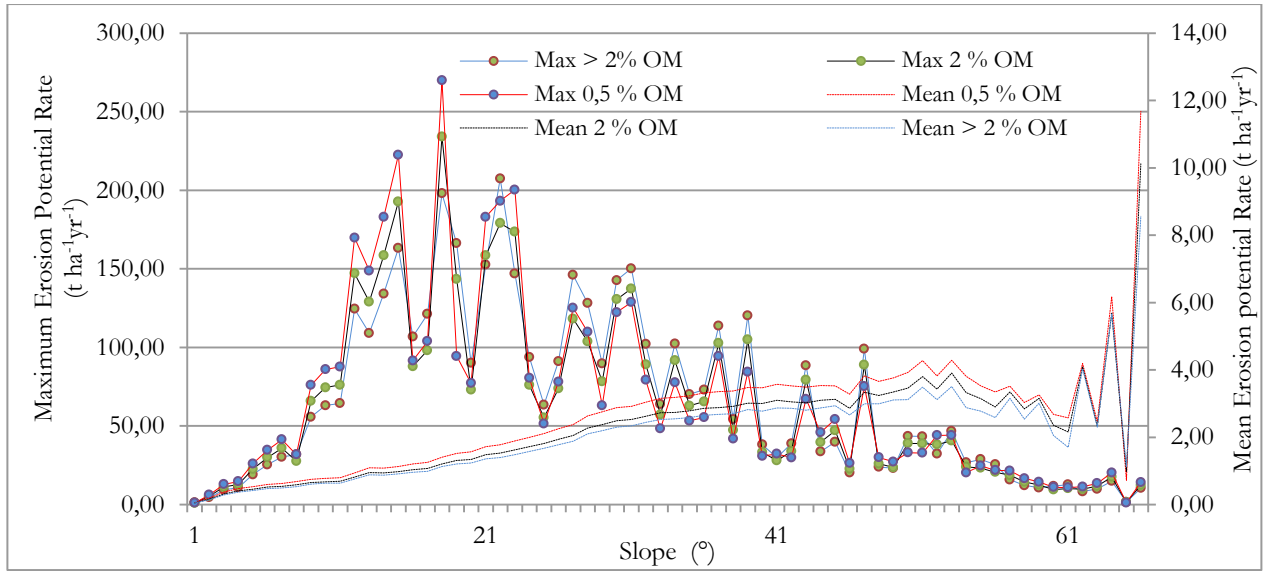


Figure 62: Soil erosion potential rate following OM with stripping support practice ( $t\ ha^{-1}\ yr^{-1}$ )



**Figure 63:** Soil erosion potential rate following OM with terracing support practice ( $t\ ha^{-1}\ yr^{-1}$ )

Using the attribute tables of the mapping results, information about the area (ha) that is covered by every risk class for each OM content scenario and support management practice was extracted and presented in a tabular format (Table 25). This enabled to easily compare results between the different crop management systems and soil erosion severity given in (Table 29).

**Table 25:** Potential soil erosion rate with terracing support practice with respect to OM content ( $t\ ha^{-1}\ yr^{-1}$ )

Class	Area (ha)	Area %	Min	0,5 % OM			2 % OM			>2 % OM		
				Max	Mean	Min	Max	Mean	Min	Max	Mean	
1	3547,09	59,07	0	9	3	0	8	2	0	7	2	
2	2116,73	35,52	0	26	5	0	23	4	0	20	4	
3	307,45	5,12	0	40	8	0	47	7	0	54	7	
4	15,01	0,25	5	121	25	5	98	21	2	104	20	
5	1,80	0,03	15	141	69	13	128	63	5	148	60	
6	0,60	0,01	101	207	139	87	234	140	57	270	141	

**Table 26:** Potential soil erosion rate with stripping cultivation with respect to OM content ( $t\ ha^{-1}\ yr^{-1}$ )

Class	Area (ha)	Area %	0,5 % OM			2 % OM			>2 % OM		
			Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	3547.09	59.07	0	11	4	0	9	3	0	9	3
2	2116.73	35.52	4	14	7	3	17	6	1	19	6
3	307.45	5.12	14	43	20	10	50	18	5	58	17
4	15.01	0.25	43	121	62	34	142	54	14	164	52
5	1.80	0.03	122	271	177	99	320	161	43	369	153
6	0.60	0.01	273	519	358	222	585	357	162	675	358

**Table 27:** Potential soil erosion rate with contours cultivation with respect to OM content (t. ha<sup>-1</sup>.yr<sup>-1</sup>)

Class	Area (ha)	Area %	0,5 % OM			2 % OM			>2 % OM		
			Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	3547.09	59.07	0	34	8	0	40	6	0	11	5
2	2116.73	35.52	0	105	15	0	124	13	3	39	12
3	307.45	5.12	0	199	40	0	236	35	9	116	34
4	15.01	0.25	27	606	123	23	491	107	29	328	104
5	1.80	0.03	75	705	347	63	640	315	87	738	307
6	0.60	0.01	504	1037	697	435	1170	698	323	1350	717

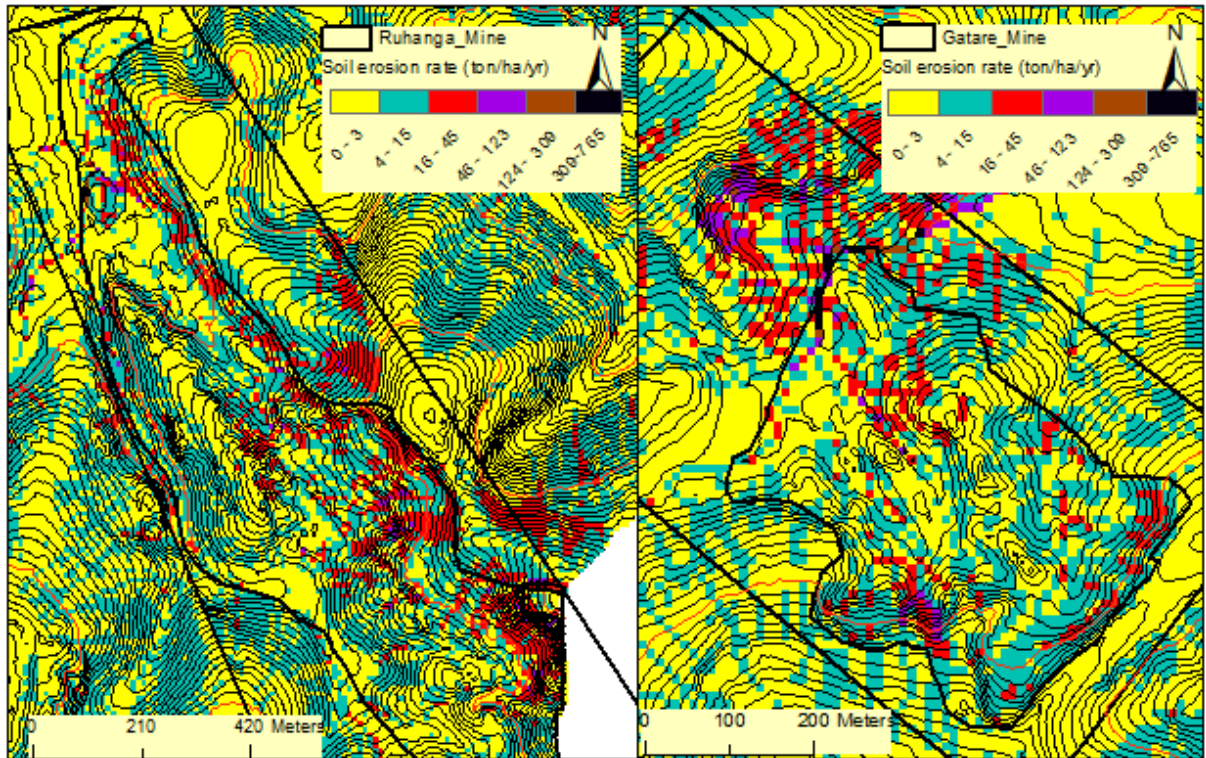
Results of scenarios summarized in tables above show that soil erosion rate change sensibly with changing OM content and support practice applied to mitigate erosion. Extensive part of the study area (59 %) especially where the slope is low (<15°) experiences soil erosion comprised between 0 and 9 t ha<sup>-1</sup> yr<sup>-1</sup>, 0 and 8 and 0 and 7 t ha<sup>-1</sup> yr<sup>-1</sup> for with terracing following different OM content, from 0.5 %, 2% and > 2% respectively. If support practice is changed to stripping cultivation for the respective OM contents, the soil erosion rates increase and range between 0 to 11, 0 to 9 and 0 to 9 t ha<sup>-1</sup> yr<sup>-1</sup>. Contours cultivation seems to be the less protective technique since for the same respective amount of OM (0.5%, 2%, >2%) soil erosion rates are high (between 0 -34, 0-40 and 0-11 t ha<sup>-1</sup> yr<sup>-1</sup>) and tend to double in order of magnitude. Comprehensively, soils with less OM content are more eroded, and increased OM reduces potential soil loss. Terrace support practice reduce soil erosion, while higher erosion rates are found on contour farming system. As it could be seen in the tables 24-26, maxima of soil erosion are found on slopes comprised between 10 and 40°, and mean values of soil erosion increases with increasing slope. But erosion rate decreases sensibly with increasing OM content combined with terracing practice. Support practices are not the only option to control erosion. They can be associated with other techniques such use the cropping with suitable rooting and leave systems for fixing and protecting soil from external erosion agents.

**Table 28:** Mean Soil Erosion Rate Potential (t ha<sup>-1</sup> yr<sup>-1</sup>) based on different scenario

Support practice technique	OM content		
	0,5%	2%	>2%
	(t ha <sup>-1</sup> yr <sup>-1</sup> )	(t ha <sup>-1</sup> yr <sup>-1</sup> )	(t ha <sup>-1</sup> yr <sup>-1</sup> )
Contour	105.6	94.4	91.8
Strip	53.4	48.0	45.8
Terrace	21.2	18.8	17.8

Spots of high sediments outputs over the studied mine, are highlighted in Figure 64 However, if we consider the contributing area of of the each mine and the field results of soils as measured in the laboratory, It appears that Gatere mine produces more sediments than (Figure 65).





**Figure 64:** Spatial distribution of soil erosion risk in Ruhanga and Gatare Mines

The reclassification of soil erosion values into three numerical ranges gives the results summarized in Table 29.

**Table 29:** Soil erosion severity ( $t\ ha^{-1}\ yr^{-1}$ )

Erosion severity zone	Numeric range	Percentage
Slight	0-10	52,41
Moderate	10-30	36,57
Very severe	>30	<10

The spatial prediction of soil loss potential in the respective catchments of the Gatumba watershed was estimated, to have an overview of unvisited locations in terms of erosion risks. When applied to whole catchments, it was obvious that high quantities of sediments were mainly produced in mines which have more extended contributing areas, and/or where mining operations are likely to be more active. By order of soil loss magnitude, Upper Kibilira, Kirombozi head the list, followed by Gisuma and Kavugangoma respectively. Elevated quantities of sediments in lower Kibilira could be interpreted as resulting from the concentration of over flows (Figure 66).

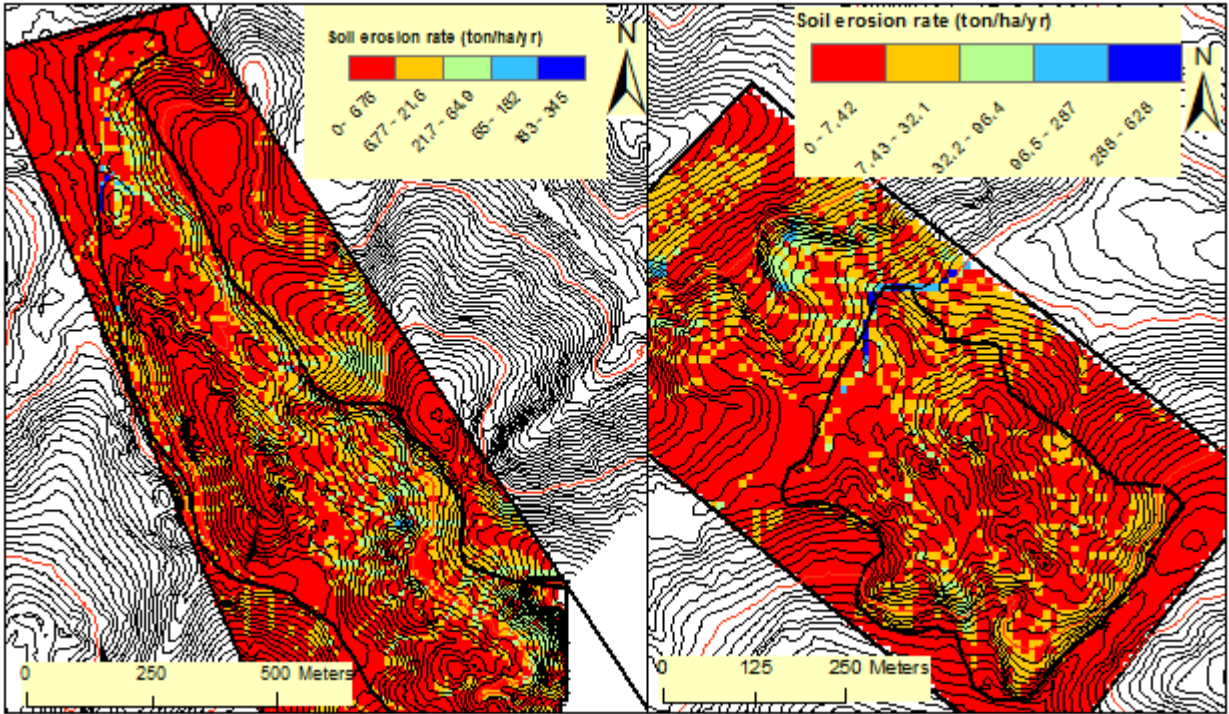


Figure 65: Soil erosion rates in Ruhanga and Gatare mines

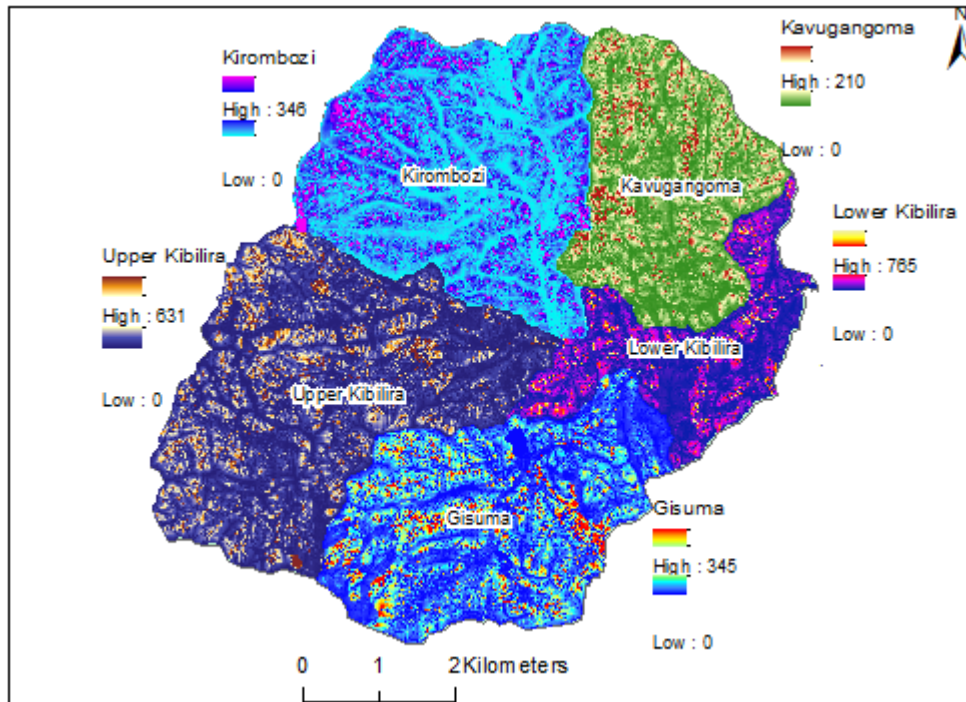


Figure 66: The magnitude soil loss in catchments of the Gatumba watershed



## 5. Discussion

### 5.1 Subcatchments analysis

Understanding geomorphic processes associated within mining sites at a watershed scale is of prime importance in developing stabilization strategies and soil erosion control. Therefore geomorphic factors and processes must be explicitly incorporated in Environmental Impact Assessment (EIA)(Cendrero & Panizza, 1997). They recognize however that this important discipline is ignored, because manuals describing EIA methods and procedures often disregard or consider very superficially geomorphic factors, even in the case of projects which may imply important modifications of landforms.

In relation of results, the watershed was classified in slope classes to which are allocated specific management or planning. Similar study has been conducted by Kevers and Ostyn (Ilunga, 1998) in Kabale-Mwenga region, Eastern DR-Congo which is densely populated like the western Rwanda. Based on the slope, they classified land into 5 slope classes:

- 0-5% (0-2°) Class I (terrain with normal productivity without soil erosion control practices. Soils are not degraded);
- 5-12% (2-7°) Class II (terrain with normal productivity, but which requires minor correction to control soil erosion.
- 12-25% (7-15°) Class III (terrain with normal productivity but which requires major correction to control soil erosion (terrain relatively high degraded)
- 25-45 % (15-26°) Class IV (terrain with poor productivity either because of thin arable soil layer or soil are highly degraded
- >45% (> 26°) No manageable terrain ,

Based on these criteria, slopes of the studied watershed shown in Figure 22 were reclassified into 3 classes (Table 29) depending on their manageability:

**Table 30:** Slope classes of the Gatumba watershed in terms of management

Slope Class (°)	Total Area (ha)	% Total Slope	Category of the terrain
0-15	1679.11	28.6	Easily manageable
15 -35	4043.3	66.8	Difficultly manageable
>35	272.95	4.6	Not manageable
Total	6004.9	100	

In the same line, researches highlight the role of characterising the watershed as a geomorphic unit supporting various assessable factors, for a better EIA (Umrikar et al., 2013). They state that the size of watershed and associated slopes, the shape, and type of drainage pattern decide the sites of erosion and deposition, extent of regolith, recharge and discharge, type of groundwater regime, nature and residence, and time of runoffs concentration. The shape of the watershed not only has a great bearing on the evolution history of the drainage, which in turn decides the characteristics of surface, subsurface and groundwater runoff (Karamouz et al., 2013), but also decides the areas favourable for groundwater recharge and discharge (Umrikar et al., 2013). Thus soil properties and catchments, as well as other factors controlling soil erosion, are interrelated and need to be considered when analysing geomorphic processes. Reference made to table 11, the compactness coefficient of catchments constituting the Gatumba watershed comprise between 1.33 and 1.41. This range should be regarded as reflecting variability in time to concentration of runoff and flooding in the respective sub-catchments, which are rapid with smaller coefficient values. Also, localized presence of knicks and potholes along the riverbed identified during the field study indicates that geomorphic development in the area is controlled by geological structures.

Generally, soil texture of the study area is mostly clayey. The high content in clay could be related to bed rocks which are metasediments (schist formation on extensive part of the study area), but also suggests a more or less advanced weathering, owing mainly to climate condition which is rainy for a long period of the year, with relatively warm temperatures. This soil texture is common with Ultisols development which is of intermediate weathering between Alfisols and Oxisols (Tan, 2005). In opposite to Alfisols which are less weathered and contain much amount of primary minerals in temperate or semi-arid climates, and Oxisols which reflect the more advanced (or total) weathered primary minerals under the humid and warm climate, Ultisols as connoted by the prefix “*Uti*” which means extreme leaching” are, according to USDA classification, one of the 12 soil orders seen as the intermediate product of continuous weathering of mineral in a humid and temperate climate. Resulting red clayey soils have less than 10% weatherable minerals in the extreme top layer of soil, and have less than 35% base saturation throughout the soil. Ultisols occur under almost any type of tropical vegetation (Van Wambeke, 1992). Their acidity links them to high-precipitation regions or to areas with highly concentrated seasonal rainfall that produces strong leaching.

## 5.2 Local impacts of SSOM on soil properties

The interdependency and variability of soil properties in mined sites are discussed in the following. Although physical ones have been much more investigated, soil organic matter content (OM) was considered because it influences most of soil properties. As referred to size particles of soil, such as sand (2.0-0.05 mm), silt (0.05-0.002 mm) and clay (<0.002 mm), the soil texture of the study area, mostly clayey (Clay loam, silt clay loam), is a conducive factor for a successful reclamation of the Gatumba mines. With often more than 20% clay content, the literature confirms that such fine textured soil has high potential together with OM to build-up well aggregated and structured soils (Brady and Weil, 2014). As described so far, the shortage or depletion in OM within areas of intensive land use -mine sites – (0.80 to 2.40 % in average) than in control sites (1.20 to 2.50 % in average) could be explained to result from the aeration due to the exposition of soils (Bot & Benites, 2005) as discussed in the next paragraphs. The study showed however that reclamation site located in Ruhanga mine presents relatively high OM which could reach 4.48% on some location. This suggests that there may be an increase of OM when good farm management is practiced and organic manure and compost are used (Buringh, 1984).

Soil texture is extensively described in many literatures, as being a stable and inherent soil property which is not likely to change with normal soil management, but strongly influences other soil properties. Viewed in this context and referring for instance to reclamation site of Ruhanga mine, where soil amendment increased significantly OM, and based on several literatures we can conclude that properties of soils (e.g. CEC) and nutrients, although not studied in this project, may improve. On one hand there are some soil components (e.g. texture) which are static and don't need to be supplied; and on the other hand some soil components (e.g. organic matter) are depleted by land use and can be supplied. This is in line with the statement according to which attributes of inherent soil quality (e.g. soil texture) are mainly viewed as almost static and usually show little change over time. The benefits of smaller sized soil texture together with OM have been demonstrated by several researchers (Carter, 2002). Clayey and silty soils with a well-balanced OM are renowned for their ability to improve soil aggregation (Sheoran et al., 2010; Tisdall & Oades, 1982) and to enhance CEC, nutrient availability and water holding capacity (WHC) (Tisdall & Oades, 1982).

OM content and aggregation have long been used to assess the soil quality for sustainable land management. The former is a dynamic soil quality encompassing those soil properties that can change over relatively short time period in response to human use and management and that are strongly influenced by agronomic practices (Carter, 2002; Smyth & Dumanski, 1995). Many studies suggested the

critical lower limit of OM content as 2% for acidic (pH between 5.5. and 7.5). In Gatumba, soil pH ranges from 3.7 to 5.4 (0.1 M CaCl<sub>2</sub>) and from 4.7 to 6.0 (deionized water) across soil units and depths (Nieder et al., 2008). This value could be placed below this limit. A rule of thumb of 2 % Carbon (~3.448 % OM) in soils of England and Wales, below which soils should be considered unstable (Greenland et al., 1975). Concentration of OM in soils is primarily related to climate and vegetation, to soil texture (clay content) and to soil drainage (Shepherd et al., 2002) but also to land uses. The low content in OM observed on the study area (generally <2% on extensive part of studied mine sites) could be partially explained by intensive land use. Many researchers attest that all human practices that expose the ground, for instance mining and cultivation, cause oxidation of soil organic matter so that levels decline more rapidly (Bot & Benites, 2005), which in turn impact negatively on soil aggregation. This could mostly explain the low to very low rating of soil aggregation. As shown by results, most of soils rate below 13 % of SSA. This percentage is a very low rating for aggregates that are stable to wetting given in table 22 (Hazelton & Murphy, 2007).

The provision of well-balanced OM improves functionality of soil physical properties. Soil OM decreases bulk density by dilution of the denser mineral fraction of the soil and improve water holding capacity (Shepherd et al., 2002; Wallingford et al., 1975), directly by increasing the specific surface area of the soil (Gupta et al., 1977). Positive correlation between OM content and aggregate stability has been reported (Swift and Chaney, 1984). Aggregation is generally increased so that the total number of pores is increased (Pagliai, et al., 1981) and soil bulk density (BD) is decreased so that pore size distribution is changed (Khaleel et al., 1981). Thus decrease in OM is accompanied by a decrease in number of stable aggregates of soils and dispersion of clay particles (Tisdall & Oades, 1982). Both macro aggregate stability and micro-aggregate stability are improved. The former is largely responsible for macro porosity, which determines soil drainage rate and aeration; it changes seasonally and is often affected by cultivation and cropping regime (Dexter, 1988). Micro-aggregates are less sensitive to cropping practices than macro-aggregates (Dexter, 1988) and are responsible for crumb porosity which controls the amount of available water for vegetation (Davies & Younger, 1994). Furthermore, soil aggregation controls hydrology and reduces soil erosion potential, affect soil diffusion and the degree of nutrient availability to the soil (Sheoran et al., 2010) and constitutes a pathway of organic carbon stabilization and long term sequestration (Six et al., 2004). The improvement of soils through the provision of well-balanced OM impacts positively on the ‘water-stable aggregate’, which is the stability of soil aggregates to the action of water (Brady & Weil, 2014).

Generally, the study showed that most of BD values comprise between 1.20 and 1.55 g cm<sup>-3</sup>, locally few exceed this range up to 1.76 g cm<sup>-3</sup>. Total porosity (TP) mean values in topsoil layers range from 33 to 52 %. However, if we compare values from different plots, control sites (CS) outside of mines and ex-mine cultivated sites (CP) have lower values of BD and relatively elevated TP, which range from 1.29 to 1.58 g cm<sup>-3</sup> and from 41 to 49 % respectively. Considering the standard ranges of BD, the studied soils present higher values than those which would be expected for identified soil texture classes. Ideal BD for productive natural soil for plant growth should range from 1.1 to 1.5. It should be less or equal to 1.10 for clay loams (USDA-NRCS, 1999). However, for the clayey texture class encountered on the field, average BD ranges from 1.32 g cm<sup>-3</sup> to 1.42 g cm<sup>-3</sup>. BD of sandy loam soils identified in studied mines is 1.50 g cm<sup>-3</sup>, while the ideal one should be less than 1.40 g cm<sup>-3</sup> for sandy clay loam.

Reasons of such changes in BD which is variably distributed on the study area are highlighted in the following. BD is the key physical property of any porous material which changes and impacts on TP in response to disturbance (FAO, 2015). This implies either compaction or inappropriate soil management practices. If the BD of soil is fixed, the relative amount of pore space is also fixed (Dane & Hopmans, 2002). On the studied sites a relative homogeneous distribution of BD was observed on control sites, whereas it is variably distributed on mine sites. As showed by results, the locally increase in BD which may imply loss of available soil rooting depth in mines could be attributed to structural compaction and loss of well matured topsoil layers resulting from mining. Structural compaction in studied mines could be associated with the destruction of soil aggregates as rather a consequence of OM depletion than engine compaction. Compaction and loss of topsoils directly limit plant growth, as most species are unable to extend roots effectively through high BD. Denser soil can't sustain vigorous plant communities due to shortage in plant available water poor aeration, slow movement of nutrients and water and built-up of toxic gases and root exudates (Brady & Weil, 2014). Day and Bassuk (1994) state however that there is no "threshold" level below which roots grow normally. Instead, there is a continuum of root restriction: any increase in soil compaction may reduce plant growth. They preferred to use the terms "*growth-limiting*" or "*maximum allowable*" BD to describe the upper end of that continuum where root growth is severely curtailed or even halts altogether (Day & Bassuk, 1994).

Although relatively elevated, these values are yet physical acceptable conditions for an easy manageability and improvement for plant growth. As OM play a key role in improving soil aggregation (structure) which impacts positively TP, many researchers asserts that soil properties such as optimum balance of air and

water contents are improved. The low rate of OM content explains partially low water holding capacity of soil, whereas the elevated clay content could be associated with the low PAWC.

Mining operators need to be aware or bear in mind that soil is a vital natural resource that is non-renewable on the human time scale (Jenny, 1981). It is a living, dynamic, natural body that plays many key roles in terrestrial ecosystems for the well-being of humankind and animals, and the major source of most of our food production (Jenny, 1981). Furthermore, the reclamation of degraded mined soils and maintenance of their health is essential not only for sustained SSOM operation but also for stabilizing the landscape and maintaining the ecosystem functionality.

### **5.3 Impact on soil hydraulic properties**

#### **5.3.1 Soil water holding characteristics**

Although water content is the most commonly performed kind of soil analysis, it is not an independent variable in the physical sense (Dane & Hopmans, 2002). The moisture tensions applied during experiment are pF 1/3 bar for WHC and pF 15 for PWP, with the aimed to determine the AWC. As shown in the results, WHC, PWP and AWC on both studied mines vary from site to another, but the variation is not significant. 60 % of Ruhanga series showed the highest WHC  $\geq 20$  %. Also WHC varies within different plots under different managements, 23.66 % on control sites (CS), 25.37 % on Ex-mine cultivated site (CP), and from 26.66 to 27.27 % on Ex-mine reclamation (ERS) and Ex-mine self-recovering site (SR). The lowest WHC was found on SR with values comprised between 9.67. In Ruhanga mine average WHC, PWP and AWC represent 20.43 %, 18.07% and 2.37 % respectively, while in Gatare their values are 20.35, 18.23 and 2.13 %. Lowest values were found on some sites of Gatare mine with 18.89, 17.22 and 1.68 %. What interests more is the AWC boundaries where 85% of moisture comprise in average between 2% and 3 %; and all samples showed a low AWC (lower than 4%). This percentage of AWC on all sites including control sites, places lower than 5 %, which is the limit value recommended for the plant growth (Maiti et al., 2002).

In connection with soil moisture values as obtained by analyses and acceptable limits described in the precedent paragraph, many authors state however, that the moisture content in the soil is a fluctuating property which is influenced by the amount of OM, land use such (e.g. mining), time of sampling, soil texture and thickness of litter layers on mine site surface (Charman & Roper, 2000). Results suggest that moisture and variability in distribution over the studied sites described above could be interpreted as resulting more from levels of OM content and built-up of soil properties than to mechanical (engine)

compaction, or time of sampling since sampling was performed during the same season. As already discussed in the previous paragraph, structural compaction of soils could not be however excluded because the depletion of OM content is accompanied by destruction of soil aggregates. As consequence, there is packing of soils which increase soil density which is accompanied by reduction of soil potential to hold water due to the reduction of soil pores. The role of OM and the effect of soil texture on soil moisture have been demonstrated by several authors. The effect of OM changes for wetter moisture contents vary with the soil texture, particularly clay. Soils with gravel-size particles ( $>2\text{mm}$ ) lose a portion of their water holding and conductance capacity (Saxton et al., 1986). Water content at high tensions (15bar) is determined by texture, thus there is minimal influence by aggregation and OM (Saxton et al., 1986; Haynes et al., 1991). Thus shortage in OM impacts negatively several attributes of soils. Chemically, it is the source of nutrient for plant especially Nitrogen (N) and Sulphur (S) in soils. Furthermore, increased OM generally produces a soil with increased water holding capacity and conductivity, largely as a result of its influence on soil aggregation and associated pore space (Tan, 2005). We understand by there that soil properties are interrelated; modifying one will create a cascade of several unexpected geomorphic processes.

### **5.3.2 Soil water infiltration**

In the previous chapter, we noticed that within mines, infiltration rates (IRs) as well as infiltration curves varied between soils under different uses. Analyses showed that IRs on approximately 70% of field tested sites within mines have between very slow to slow categories. Such alteration of water infiltration is related with the degradation of macro-aggregates and micro-aggregates of soils (Kay, 1990). The former is largely responsible for macro porosity, which determines soil drainage rate and aeration, but in this context was altered. Micro-aggregates are less sensitive to cropping practices than macro-aggregates (Dexter, 1988), and are responsible for crumb porosity which controls the amount of available water for vegetation (Davies & Younger, 1994). However, although micro-aggregates are affected, this can rather be demonstrated by extraction of soil water using pressure extractor than by a simple infiltration process experiment. Also, the moderate ranges of IRs were found on control sites whereas they were slow on ex-mined cultivated and reclamation sites. On one location of ex-mine self-recovering site however, IR and infiltration process were found to be excessively rapid as shown by infiltration curve (Figure 45), fluctuated. This situation could be related to both degradation soil structures and development of mechanical porosity, described in the next paragraphs. In general, infiltration experiments were of short time, up to 30 minutes. Many researchers state that the duration of testing infiltration depends upon the information desired. Most infiltration tests are of short duration to simulate the effects of rainfall or the

application of irrigation water. Even then, the rate usually decreases with time of application (Johnson et al., 1987).

Infiltration is much more dependent on soil properties, and plays a major role in terms of geomorphic processes. Soil texture and OM improves infiltration property. OM promotes the development of stable soil structures by increasing granulation and pore spaces mostly in clay texture soil (Haynes et al., 1991). Furthermore, infiltration is concerned with the provision of soil conditions, which enables a better movement of water and gas and allow plants to make optimum use of nutrients (Hillel, 2004). From the same stand points, this special case of soil water movement holds a pivotal role in geomorphic dynamics for two reasons: (i) it is the critical process that divides precipitation between runoff which may participate in geomorphic processes (such as soil erosion) and infiltration which may add to stored soil water for plant growth, or may leach through the soil and drain to groundwater (Geeves et al., 2000), (ii) infiltration property is affected by different land use practices in different ways.

During field experiments, infiltration was slow or very slow, or fluctuated on some experimental sites. This would be associated with soil structures developed in subsurface soil layers or destruction of aggregates that releases fine particles which seal soil pores. As a consequence, the soil structure, initially made-up by combination or arrangement of primary soil particles into aggregates is destroyed. This impacts negatively on soil pores' connectivity. Either pores of surface soil are sealed and disconnected to subsurface soil pores, or released fines are washed out from topsoil layers downwards, forming in subsoils less permeable structures (Yimer et al., 2008). Infiltration should be therefore soil or structure controlled (Yimer et al., 2008). In the same line, Wilding et al. (2012) relate the fluctuation of infiltration process to possible existence of multiple buffers at the base of the soils to restrict the water movement, including partially cemented structures, infilling of joints and fracture planes of the soil, bedrock interface. According to Toy et al. (2002), such situation could result from the variability of rainfall intensity and/or the spatial (lateral or vertical) variability of soil properties that affect the infiltration process. The decrease or fluctuation of infiltration from an initial rate could be associated with the gradual deterioration of soil structure and the partial sealing of the profile by the formation of surface crust (Hillel, 2004). It can also result from the detachment and migration of pore-blocking particles, from swelling of clay, as well as from entrapment of air bubbles or the bulk compression of the air originally present in the soil if it is prevented from escaping its displacement by incoming water (Hillel, 2004)

Thus, it is reasonably understandable that such alteration of infiltration process as shown by field experiments could be also related to alteration of pores' connectivity which is another intrinsic soil



structure property often affected by land uses. Many researches attest that alteration of pores' connectivity affects significantly the transport of soil water and soluble minerals, and gases (Alaoui et al., 2011). Both macroporosity (pores developed by the soil fauna, plant roots, cracks and fissures, natural soil pipes) and microporosity (essentially developed by the aggregation soil forming process resulting from built-up of OM and soil texture) are both negatively affected, due to cut of vegetation and collapse of soil mineral particles as a consequence of OM depletion (Beven & Germann, 1982). As the proportion of large pores and their connectivity decreases (Hillel, 2004), overflow occurs and subsoil is restricted from water, nutrients and gases.

The presence of cracks and fissures can significantly affect water and solute movement in soils by creating non uniform velocity fields with spatially variable flows referred to as preferential flow (Novak, et al., 2000). It was found that the infiltration rate decreases with increasing clay content (Free et al., 1940). However, desiccation structure in the sediments may cause difficulties in determining the infiltration rate. Heavy clay soil may crack during drying, and considerable penetration may result upon the first application of water (Johnson, et al., 1987). As the soil adjoining the cracks is wetted, however, it swells and closes the cracks, so that infiltration becomes very slow. The term "preferential flow" is used to mean the distribution of flow via distinct pathways that constitute only the fraction or sometimes a small fraction of the soil total volume (Beven & Germann, 1982). Pores formed by burrowing animals, or by plant roots or cracks and fissures formed by shrinkage in clayey soil or by chemical weathering of the bed rock material. In the same line, the presence of cracks and fissures can significantly affect water and solute movement in soils by creating non uniform velocity fields with spatially variable flows referred to as preferential flow (Novak et al., 2000). Also, natural soil pipes can form as a result of the erosive action of subsurface flows in highly permeable and relatively non-cohesive soil materials when subjected to high hydraulic gradients (Wisler & Bratter, 1959).

During field study, fissures have been locally identified around pit edges. The existence of cracks, which is mostly caused by shrinkage as a result of drought, could be excluded because field experiments have been conducted during rainy season when soil is supposed to be wet. Encountered situation could have a more specific explanation. As the removal of soils and rocks consecutive to mining weakens the whole fabric of adjacent structures, the cohesiveness of soils decreases, which sometimes results in fissures. Depending on the stage of fissure development and because of surface erosion, it could be possible that **deep** fissures are masked by surface covering sediment. This could explain partially results of our field infiltration experiment, where on some location water infiltrated slow at the beginning and few times after infiltration

became faster before it reaches its steady infiltration rate. If subjected to alternation of infiltration water pressures, or alternating wetting-desiccation, fissures can more develop and ultimate constitute the planes of further shallow landslide. In view of what is discussed in the previous paragraph so far, there is a transition from naturally formed soil structures to degradation soil forming structures with intensive land uses (Arocena et al., 2012). They report however that degraded structures of soils of mined sites can be improved with proper reclamation strategies and addition of organic amendments.

#### **5.4 Soil erosion risk**

The universal Soil Loss Equation (RUSLE) approach with the use of Geographic Information System (GIS) spatial modelling enabled to quantitatively and qualitatively assess the erosion risk for the soils of the Gatumba watershed. Despite some uncertainties regarding RUSLE, such as the overestimation of soil loss on plots of low erosion rates and the underestimation of soil loss on plots with high erosion rates (Trabucchi et al., 2012), the model remains however useful and easier for assessing soil erosion because it requires data that are relatively common and easy to be processed with GIS.

Reference made to Figures 64-66, high potential soil erosion spots are located in mine sites. The model showed differences in soil erosion risk in different sub-catchments of Gatumba watershed. In addition to natural condition such as steep slopes, and anthropogenic activities which may intensify erosion process, the position of the mine within the catchment may explain partially differences in soil loss magnitude. Soil loss potentials are low in Kirombozi and Kavugangoma catchments where Nkokwe and Nganzo mines are located. These mines are located at the far end upslope where contributing areas are less extended. The more extended the upstream catchment in relation to mine, the more the rainwater is collected which will have increasing capacity of producing and/or relocating sediment downstream.

Rainfall erosivity (R) and topography (LS) are regarded as the primary factors of soil erosion, but also the intensity of land uses specifically agriculture and mining may enhance considerably natural processes running on the studied area. The various parameters influencing these processes include vegetative cover, soil physical and chemical properties. Also, the management practices of such areas would determine the resilience or the vulnerability of the site and soils to erosive agents. To obtain R-factor values for the RUSLE model, high resolution rainfall measurements at a small time step would be required as well as an accurate computation of R of each storm (Onori et al., 2006). Equation (16) and the simplified moving weighted average method (equation 31) were used in this work to overcome the lack of detailed rainfall data.

Different RUSLE factors contribute each at relatively variable levels. Although the erodibility (K-factor) was estimated based on a general relationship of soil texture and organic matter within the mine sites, outside of mines corresponding values were assigned based on soil texture and parent material as described in the methodology. To avoid the overestimation of the support practice (P) and land cover (C) factors, different corresponding indices were assigned based on tillage system and slope, and land cover respectively. A first visual interpretation attribute however, the magnitude of soil erosion to topography and climate, and the intensity of land use respectively. K factor could be also assimilated to land use intensification since most of agriculture farms are of nonstop cropping, which might result in depletion of OM content if adequate balance is not constantly maintained.

The LS and R factor seems to be the dominant driver for explaining the elevated erosion rates in the area, whereas P is considered aggravating or mitigating factor. Although the variation in erosion rate cannot be demonstrated based on contrasting topography, the generally steepened slope all over the catchment as shown in Figure 54 is plausible. These areas are the most sensitive to erosion, and correspond primarily to the hillsides which are cultivated mostly over the long period of the year.

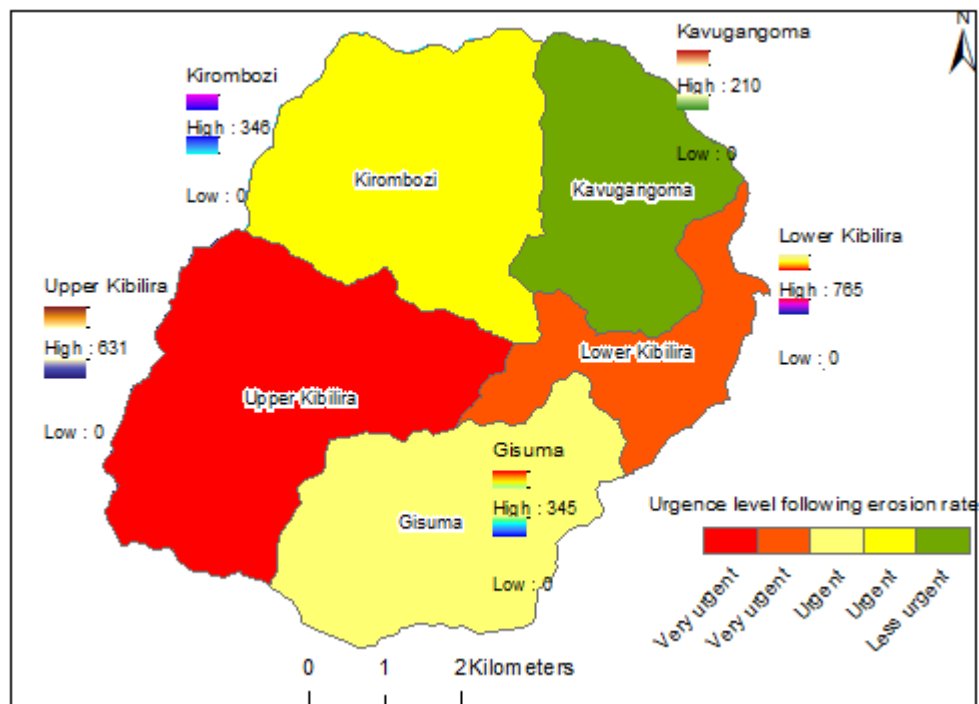
Although sediment yield delivery was not studied, the type of connection of slope may play a major role in terms of sediment relocation and redistribution. This could be explained based on the turbidity observed in streams of catchments hosting the mines: sediments transferred from slope or mines directly to stream channel may be relocated far downstream and potentially contribute significantly to siltation and turbidity. Slopes disconnected to stream transfer their output to downslope depression or alluvial plains, where they may actually overlay natural soil structures.

When compared to the R factor values of uplands of Malaysia (Teh et al., 2014), which were of very high erosivity ( $699 < R < 951 \text{ MJ mm ha}^{-1} \text{ hr}^{-1} \text{ yr}^{-1}$ ), the R values ( $266 - 573 \text{ MJ mm ha}^{-1} \text{ hr}^{-1} \text{ yr}^{-1}$ ) showed that, climatologically the Gatumba catchment has intermediate to high erosion potential, since erosivity does not exceed 600 ( $266 - 573 \text{ MJ mm. ha}^{-1} \text{ hr}^{-1} \text{ yr}^{-1}$ ). However, in spite of showing intermediate to high erosivity values, R factor is held for playing a major role in soil erosion because the rainfall is extended over the long period of the year. Furthermore, despite the intermediate R factor values, erosivity risk increases when the occurrence of unusual storm conditions occurs (Bayramin et al., 2006). Their argument was based on the frequency analysis performed with the Modified Fournier Index (MFI). Region experiencing low rainfall can record highest erosivity potentials. In Europe for instance, the highest rainfall erosivity risk is identified in areas with low annual mean precipitation. Highly erosive rainfall, for instance, hits long-period dry soils, in the Mediterranean region, which usually causes great damage and is connected to a very

high flood risk. Furthermore, high rainfall erosivity is likely to coincide with the seasonal cropping periods, when ground is being prepared for seeding and vegetative cover is not enough developed yet to protect the soil. For the case of Gatumba, the R factor may play an important role in high sediment delivery when high magnitude rainfall coincides with intensive mining operations.

Many studies have shown that the K factor mostly represented by organic matter had a great importance on soil erodibility due to its regulatory roles over numerous physical soil properties like, aggregate stability, bulk density, pH, hydraulic conductivity and erosion susceptibility (Teh, et al., 2014). The provision of adequate organic matter content improves many attributes of the soil, such as increased porosity, and soil aggregation and decreased bulk density.

The actual soil erosion risk was  $27 \text{ t ha}^{-1} \text{ yr}^{-1}$  in average. The estimation of soil loss is in the same order of magnitude as other studies. In northern highlands of Ethiopia, the average annual soil loss was  $9.63 \text{ t ha}^{-1} \text{ yr}^{-1}$  (Tripathi & Raghuwanshi, 2003). Loss of soil with average of  $20 \text{ t ha}^{-1} \text{ yr}^{-1}$  was estimated in highlands of Ethiopia and Eritrea; and measured amount of more than  $300 \text{ t ha}^{-1} \text{ yr}^{-1}$  on specific plots (Shiferaw, 2011). The author found an average annual soil loss of about  $27 \text{ t ha}^{-1} \text{ yr}^{-1}$  for the Woreda watershed in Ethiopia.



**Figure 67:** Urgency level of erosion control practice in sub-catchments of the Gatumba watershed

Although standards for defining soil loss tolerance (T) are not defined yet for individual regions of Rwanda, the soil erosion potential in the study area is higher than guidelines for T value assignment

suggested by USDA-NRCS described in Liu et al. (2009). According to the technologic manual of soil and water conservation in Changjiang basin, T was set at  $10 \text{ t ha}^{-1} \text{ yr}^{-1}$ . Based on what is discussed so far, the Figure 67 was developed in order to classify the catchments in urgency levels depending on erosion rates. The urgency reflects the severity or intensity of soil loss which could serve as a guide to set priority in allocating mitigation measures.

## 5.5 Suitability of the study area for stabilization

Almost all soils have intermediate properties and plot between U-line and A-line. The area between the U-line and A-line boundary is stable and suitable enough for stabilization if other conditions are met.

**Table 31:** Atterberg Limits and their expansive rating and shrink-swell potential

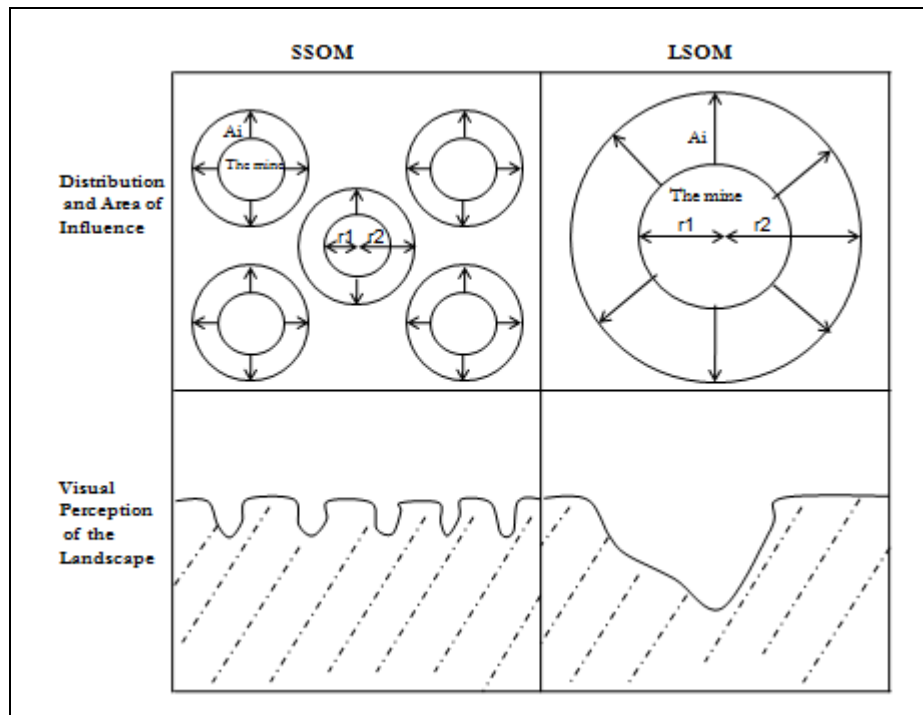
(a) Expansive rating		(b) LL, PI and Shrink-swell Potential				
Linear shrinkage %	Expansive Rating	Linear Shrinkage	Liquid Limit	P. Index	Shrink-Swell Potential	
0-12	Non-critical	0-13	$\leq 45$	$\leq 25$	Low	
12-17	Marginal	13-17	45-55	25-35	Medium	
17-22	Critical	17-21	55-75	35-45	High	
>22	Very critical	>21	>75	>45	Very high	
Non-critical generally refers to soils where the shrink-swell potential is sufficiently low that no problems are expected with constructed infrastructures. Critical generally refers to soils where the shrink-swell potential is sufficiently high that specific design criteria need to be incorporated in building foundations to prevent movement problems.		(c) Climate and Shrink-swell Potential				
		Linear Shrinkage				
		Arid to semi-arid climate		Humid Climate		Shrink-swell potential
		0-5		0-12		Low
		5-12		12-18		Moderate
>12		>18		High		

Based on boundaries suggested by different researchers summarized in table 30, the linear shrinkage for all samples comprises between 6.7 and 10. This range has a non-critical expansive rating and low shrink-swell potential (Hicks, 2007), and could better suited for stabilization structures. They would be stable enough for stabilization processes to be applied if other factors are favourable like slope angle, etc.

## 5.6 Landscape development in mine sites

The literature showed that geomorphic processes associated with small-scale opencast mining (SSOM) and resulting landforms have not been yet studied, and because of that rare restoration projects are recently considering to have resulting landscape on reclamation agenda. One of reason probably due to the nature

of mining operations scattered over several small portion of lands whose impression tends to minimize the impacts, in opposite to large-scale opencast mining (LSOM) where the mined area is more bigger and apparent in the landscape. Considering these two contrasting mining sites, zones of influence can be hypothesized through a simple deduction by calculating the area of the mine ( $A_m$ ) and the area influenced by the mine ( $A_i$ ) for both LSOM and (Figure 68).



**Figure 68:** Hypothetical area of influence of SSOM versus LSOM (Byizigiro, et al. 2015)

$$i=r_2 \quad (27)$$

$$r_m(\text{radius of the mine}) = r_1; r_i = r_2 \quad (28)$$

$$\quad (29)$$

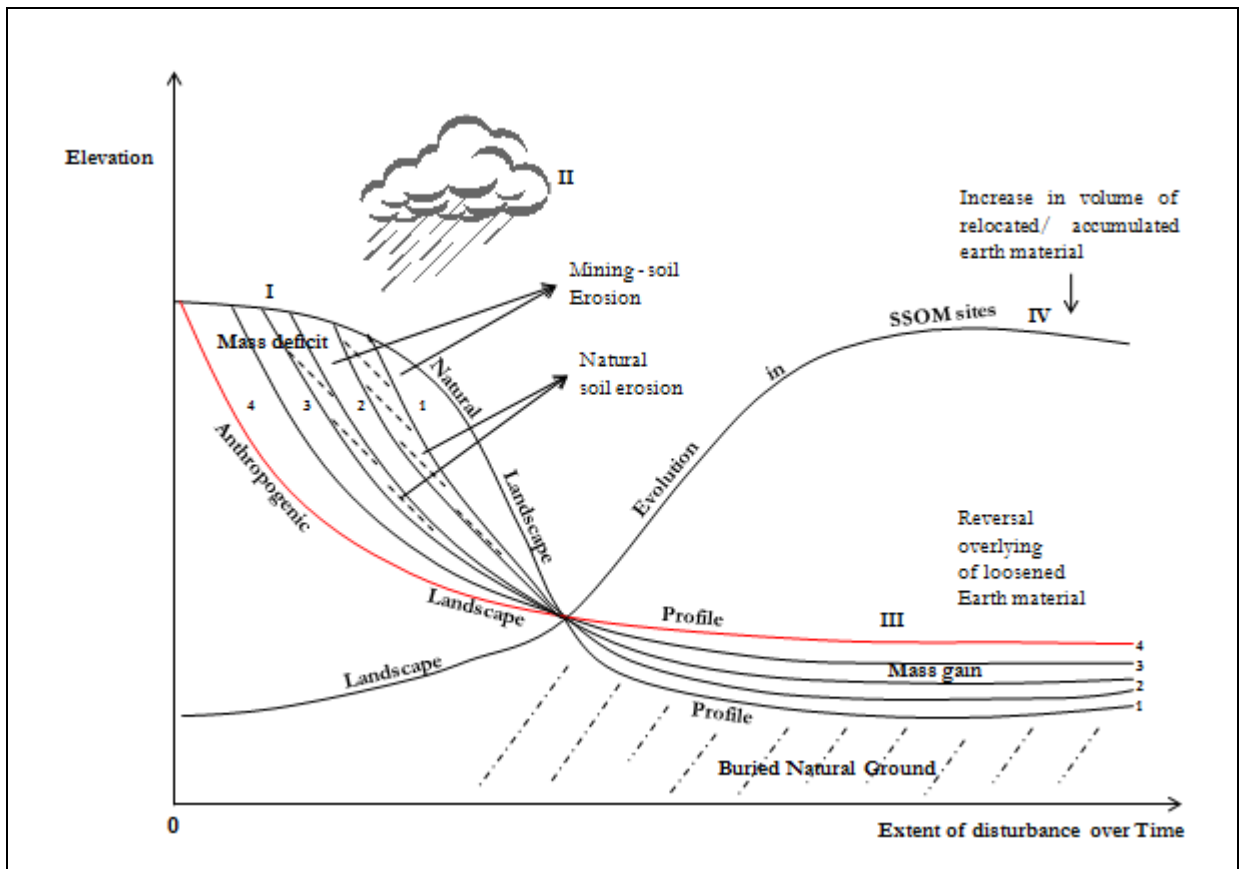
$$\quad (30)$$

$$\quad (31)$$

The idea behind the figure is that, SSOM operates on small perimeter but scattered across the land. The sum up of individual SSOM sites would relatively equal the size of LSOM one. This is a speculative idea which was not verified in this study, but that could serve as a base line for further more developed study on area of influence of SSOM. Furthermore, implementation of reclamation activities will be

compromised because efforts have to be distributed to these scattered SSOM sites, whereas LSOM offers favourable conditions for cheaper and faster restoration.

Therefore, geomorphic process in SSOM sites lead to landscape evolution which is schematically shown in Figure 70 below. This is essentially a process of levelling-off by enhanced erosion of topographic highs, and complementary deposition in topographic lows. The natural processes of soil erosion, normally controlled by natural factors such as the climate, the vegetation, the slope, the soil and the substratum, are either accelerated or altered by mining operation which results in mass deficit of soil and earth material (I) which aggravate natural erosion process (II). Commonly operating concomitantly with mining operation, the relative magnitude of natural processes on mine sites is much more noticeable during dormant phases or after decommissioning of mining activities from the site. Sometimes, mined pits on hillsides are further enlarged by mass movement (sliding or slumping), rills or gullies development.



**Figure 69:** Landscape evolution within ASM sites

I. On-site, excavation of mineral bearing ore causes gradual mass deficit (from 1 to 4) and exposes subsurface geological structures to further mass translocation by natural erosion agents II. Off-site impact includes III mass gain which reversely buries the natural ground in low-lying area

The extent of sediments spread downslope or downstream (III) largely depend on mechanisms implemented to mitigate resulting erosion process. If sediments from mined sites are not well controlled and confined, they may affect large perimeters of lands and impact negatively on land use potentials. The trend of landscape evolution will therefore consist of mass deficit on perimeters being mined and mass gain downslope where sediment and fresh earth material burry the natural ground (IV).

In connection with the statement above, geomorphologists often distinguish between hillslope and channel or low-laying area processes. Tucker and Slingerland (1994) stress that this is a useful distinction although one has to bear in mind that the transition is not always abrupt. We partially agree with Tucker's statement in the context that his argument is based on natural geomorphic processes. But in areas severely impacted by human activities, for instance mining, the transition may be even more abrupt since according to (Szabó, 2010) sediment load including soil and geological material produced by mining operation and their environmental impact increase exponentially in comparison with that produced by natural processes ones (Szabó, 2010). Furthermore, Tucker and Slingerland (1994) distinguish between processes that are driven nearly exclusively by gravitational processes, and those that involve fluid phase (water). They highlight however that, for instances landslide is gravitational phenomena but often triggered by fluid pore pressure, while debris flow is surges of mixed fluid and solid.

Thus the evolution of landscape with SSOM sites may comprehensively involve complex and interrelated processes. Hancock (2004) states post-mining landscapes need to be designed using an understanding of geomorphic landscape processes together with best practice technology (Hancock, 2004). Otherwise, restoration projects fail because topographic designs are unable to sustain functional ecosystem or because the export of sediments can affect the ecosystems downslope and also downstream of the disturbed area (Hancock, 2004). Therefore, management plans for a watershed encompassing mine sites to be rehabilitated should take into account the need to evaluate the importance of areas of sediment production and accumulation and all associated processes with respect to different uses and the potential benefits of restoring these areas, and assessing the effective value for the production of ecosystem services.



## 6 Conclusions

### 6.1 General conclusion

The concluding notes draw from consecutive chapters as discussed so far. Understanding geomorphic processes of both mining and post-mining mass movement is a basic prerequisite toward the development of control strategies of these processes and successful mine reclamation, whose mastery ultimately can result in the sustainability of the Small-Scale Opencast Mining (SSOM) sector.

The aim of the study was primarily to assess the geomorphic processes and resulting landforms typical of SSOM. These were assessed in three complementary approaches: field survey and field experiments, laboratory analyses, and soil erosion modelling. The field survey showed that the major direct processes include (i) excavation (cutting, trenching, pitting, striping, and sometimes shallow tunnelling), (ii) construction which results in features like tailings dam, mine waste piles, rock dump and terraces; and (iii) diversion of stream flow. Indirect but primary or immediate processes are mainly (i) stream siltation as a consequence of soil erosion and sedimentation, sometimes (ii) collapse of geomorphological structures as a consequence of undercutting resulting from the clogging of stream channels, rare but sometimes can happen is (iii) the subsidence if shallow galleries are developed with the comprehensive removal of earth material from shallow underground. Specific landforms emerge and the natural pathways of landscape development are altered. Landscape in SSOM is often characterised by denudation. The most conspicuous erosive features include rills, gullies, slides, topples and slumps and sometimes sinkholes. Depositional features include debris flows and tailing fans that form at the outlets of mine pit, and braided channels that develop downstream as a consequence of high sediment yield delivery. Contrary to accumulated landforms which result from dumping mostly using bulldozers, depositional ones are performed by natural processes.

The field experiments and laboratory analyses of soil properties showed that SSOM impacts on natural geomorphic processes. As discussed so far, alteration of geomorphic processes are reflected by the variability in distribution of physical and chemical properties of the soil over different experimental plots within the mines. We could argue that levels of degradation or recovery could be associated with land uses implemented on specific sites. The variability of soil texture was not much noticed over the studied mines. However, degradation of soil quality was more reflected by the shortage in OM content and low to very rating of soil aggregation over the whole sites, distribution of bulk density (BD) and total porosity (TP) in the surface soil layer. Note that the studied soil properties are variably distributed and far to be homogeneous on different experimental or sampling plots. The soil quality in areas affected by intensive

mining activity was comprehensively more altered than that in sites further away from the mine. Soil stable aggregates (SSA) were found to be more dependent of OM content: the more older and reclaimed is the site, the more are the amount of OM and soil SA.

The study showed differences in available water holding capacity (AWC) and infiltration rates (IRs) over the studied mines. AWC is more elevated in soils of Reclamation sites (ERS) followed by Ex-mine self-recovering sites (SR) than in soils of ex-mine cultivated sites (CP). Comparison of AWC of mine sites with that of control sites (CS) did not show noticeable differences. Although IR is in average low to moderate, it tends to be much more improved on CP, and ERS. SR presents the lowest IRs as described in Appendix V (Table 40). Furthermore, experiments showed that infiltration process on some locations within the mines fluctuated as shown by infiltration and accumulated curves in Figure 45. As discussed in the previous chapters, variability in AWC distribution over the nine sites could be much more influenced by the amount of OM in the respective soils and built-up of soil properties than by land use. This applies also to IRs as well. In addition, the low to very low IRs found on different mine experimental sites could be related to structural compaction resulting from depletion of OM and destruction of soil aggregates. Viewed in this context, it is possible to conclude that the build-up of OM which may readjust properties of soils requires enough time to integrate in the soil profile as discussed in this work.

Alteration of soil quality and properties described in the paragraphs above could be regarded as secondary and indirect geomorphic processes associated with SSOM that could influence strongly land use potentials. The classification of mines into different sites e.g. CP, ERS, SR as compared to CS, was mainly based on affected land uses. The ex-mine self-recovering sites, for instance, are basically more degraded and idle lands which cannot support crops. They are unused and abandoned portion of mined lands which are actually undergoing the recovering process without human intervention. CP and RS are portions of mine sites less degraded mining operation which is hoped they can be returned to immediate economical usages like agriculture if adequate reclamation strategies are implemented. Comprehensively, SSOM influences negatively land use potentials since it is accompanied by reduction of crop lands and alteration of soil quality (depletion or decrease in OM and nutrients) and properties (such as WHC or gas and soil water movement, etc.).

The Revised Universal Soil Loss Equation (RUSLE) model integrated with GIS was applied in order to assess the soil loss potentials in the study area. Required components of RUSLE were modelled using various mathematical formulae, to explore the relationship between the rainfall erosivity, soil erodibility, slope, support practices and management. Detailed data for the computation of the local R factor were not

available for the local study area. Therefore this parameter was estimated by means of weighted moving average formula. K factor was obtained from soil map of Rwanda and complemented by field study results. K factor indexes were assigned based on OM and soil texture. But for the mining site, soil erodibility (K factor) was determined based on the Proposed Alternative Soil Erodibility Factor (RFACT) formula. The GIS-based RUSLE model could be re-run by readjusting the support practice (P factor) and K factor values to assess the effect of implementing the best management plans on the resulting soil erosion potential values. This important part of the research aimed at understanding the landscape dynamics as impacted by SSOM. This was a very important and addition result which together with those summarized in the previous paragraph should be considered in developing adequate and holistic reclamation and mitigation strategies to prevent further land degradation. Results showed that spatial average of soil loss in the Gatumba watershed is  $27.45 \text{ t ha}^{-1} \text{ yr}^{-1}$  with a standard deviation of 0.891. More than 65% of land are prone to high rates of soil loss (exceeding  $10 \text{ t ha}^{-1} \text{ yr}^{-1}$ ), and an increasing soil erosion follows increasing slope and land use patterns. The maxima of soil erosion rates are found in Upper Kibilira and Gisuma catchments which are actually intensively mined. Different scenarios applied to quantify soil erosion rates showed that more the OM (from 0.5%, 2% and >2%) is increased with better support practice (from contour, strip and terrace), the soil erosion potentials are decreased linearly (Table 28).

Some limitations were encountered when developing this project. Geomorphic processes associated with SSOM appeared to be a new field of research which is scarcely addressed in literature. For this relevant references are lacking. Thus methodologies to deal with the subject were designed based on ideas emerged from discussions held with supervisors and other experts in the field of geomorphology. We used an exploratory approach which involves different methodologies to collect basic information with the view of focusing on specific themes in further and more elaborated studies. Land cover change resulting from mining in the study area was not conducted, because this needs time series data which could not be obtained during the research time frame. Furthermore, there may be some uncertainties in results obtained with RUSLE due to data used. Spatial heterogeneity mostly related to mining at catchment scales, and use of empirical data interpolated, for instance, from the closest rainfall stations may have affected the predicted values. Furthermore, the knowledge of seasonal and spatial distribution of unusual storm event conditions with high erosivity potential at local scale which were not demonstrated in this study is of immense importance for soil erosion research and management. Nevertheless, results showed that the predicted amount of soil loss using a moving weighted approach and its spatial distribution can serve as a basis for developing mitigation strategies of soil erosion and sustainable land use at watershed scale and

catchment scale as well. Another limitation is that standards for defining soil loss tolerance (I) are not defined yet for individual regions of Rwanda.

As it has been established, the objectives of the study and testable hypotheses were conformed. Furthermore, results showed that most processes leading to mitigation of geomorphic impacts cut across scientific disciplines, but they may include political and social boundaries. In view of this, the scientific community in partnership with the mining statutory authority has to develop an interdisciplinary approach and coordinated effort, as suggested in the next chapter, to address this challenge facing the SSOM sector.

## **6.2 Recommendations for further research**

Throughout the literature, it is evident that mining without an impact on environment and inhabitants of the mine's surroundings is impossible, but industrial mining strives to minimize negative effects and to improve the welfare of affected communities "green mining" (Rukazambuga, 2008).

From the research findings on Gatumba, and based on various discourses related to mining sector in Rwanda, it is evident that there is a need to move the sector towards a more responsible, industrial enterprise. The first difficulty in studying geomorphic impacts produced by SSOM is that the topic is far to be self-independent and is too wide to be treated through a single approach or expertise. This implies that suitable multidisciplinary approaches to studying the affected SSOM sites need to be identified and the protocol well designed. Various expertises such as soil science, civil and rural engineering, geomorphology and many others related with land reclamation are therefore needed. Field, laboratory study and mapping in respective fields of expertise are required before future restoration-management projects. This would help to identify level of disturbance and areas prone to high risk of erosion so as to set priority areas and develop a hierarchy ordered according to need and means.

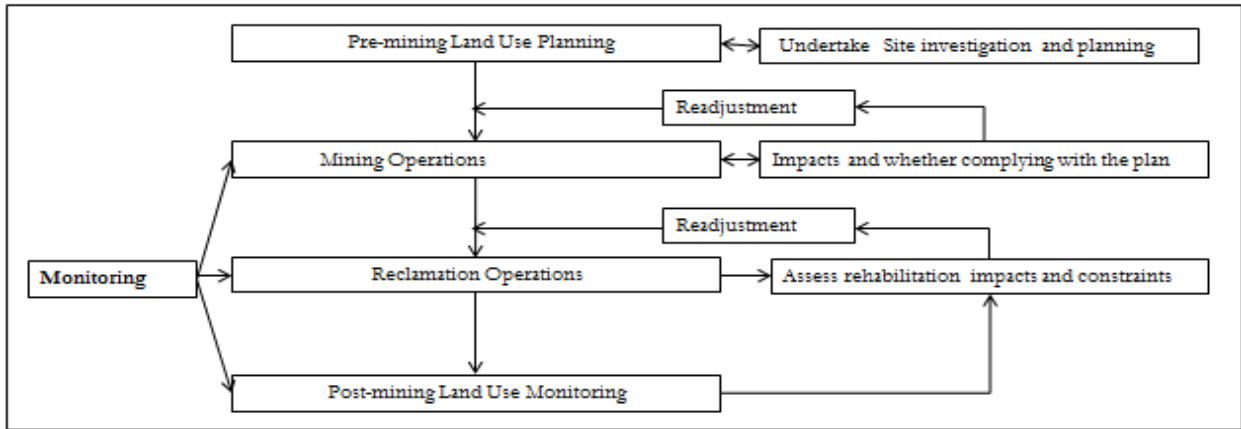
During the field study, different classes in terms of the extent or level of land deterioration within individual mines were identified. This was found to be the best approach to studying geomorphic processes and to compare levels of land degradation. However, as already mentioned in the paragraph above, the study of respective classes needs to be more detailed individually. This suggests that several researchers need to be involved in the assessment of impacts of SSOM on the basis of which alternative but more consistent reclamation strategies could be formulated. Furthermore, there is a need of more researchers on single classes identified based on the individual but complement expertise, as specified in the next paragraphs. In either orphan, abandoned and/or owned mines, different types and levels of degradation should be identified and plotted (zoning). The study showed that there are onsite and off-site

levels of degradation. These aspects need to be more strengthened in further researches and categorized in zones highly disturbed, zones strongly disturbed and zones moderately disturbed. This categorization would enable a proper allocation of mitigation tools and strategies, whether (i) to rely completely upon spontaneous recovery, or (ii) to exclusively adopt technical measures, or (iii) to combine both approaches by manipulating spontaneous recovery towards a target. This would be a prerequisite for developing proper mitigation strategies based on the specificity of individual mine sites but depending also on level of impacts within individual zones.

The different scenarios applied to study soil loss potential showed that soil erosion reduced significantly with increased OM and terrace cropping system. This is in line with almost all researches on the subject according to which increasing OM improves cohesiveness and resistance properties of soil, and reduces shear strength of runoff. For this, further investigation need to focus on improving soil structure by researching through varied experiments the best amendment, tillage system and mechanical measures suitable for stabilizing reclamation sites and improving ecological functionality. Trees, green fertilizers and manures from livestock were already recommended and are applied on several portions of abandoned mines in Rwanda, but more specialized researches by considering the specificity of each site are needed to determine the most suitable for soil fertility improvement under the nutrient recycling hypothesis, but also for collateral multipurpose functions, such as erosion control (hedgerows), fodder, fuel and construction wood.

Investigation of soil erosion potential has demonstrated that GIS based RUSLE modelling techniques is simple and low-cost tools for predicting soil erosion. Field measurements of rainfall erosion (direct measurements and simulated rainfall) are highly recommended. There is a need to study the K factor for different watersheds constituting the Western Highlands of Rwanda. Furthermore, time series data e.g. aerial photographs and DEM of good resolution could be much interesting in order to evaluate the land cover change in relation with mining and restoration.

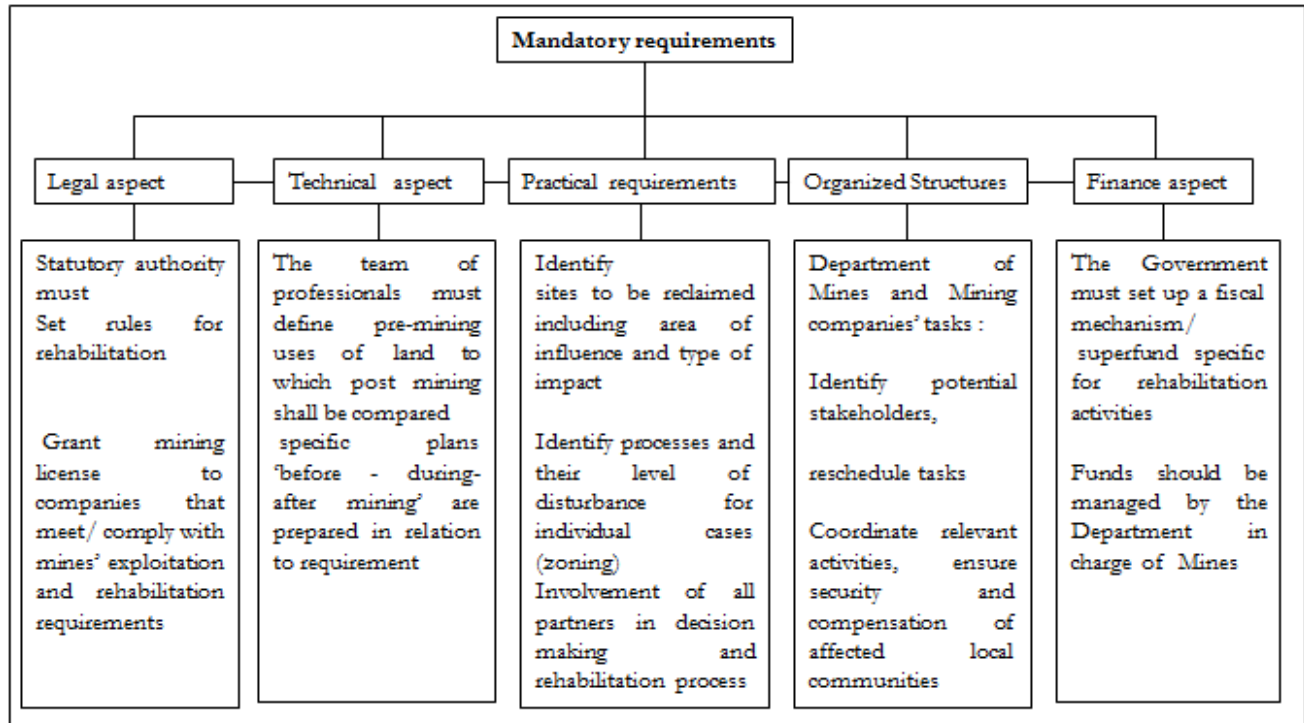
Therefore, the process of mitigating geomorphic processes resulting from SSOM and to reclaim affected lands for a natural or economically usable state should be viewed as a sustainable planning which must be implemented in consecutive steps summarized in the flowchart below (Figure 71). The setting of performance targets for each step could therefore be very interesting and may be useful in addressing SSOM issues, by revising or readjusting applied techniques.



**Figure 70:** Steps required for the sustainability of SSOM reclamation

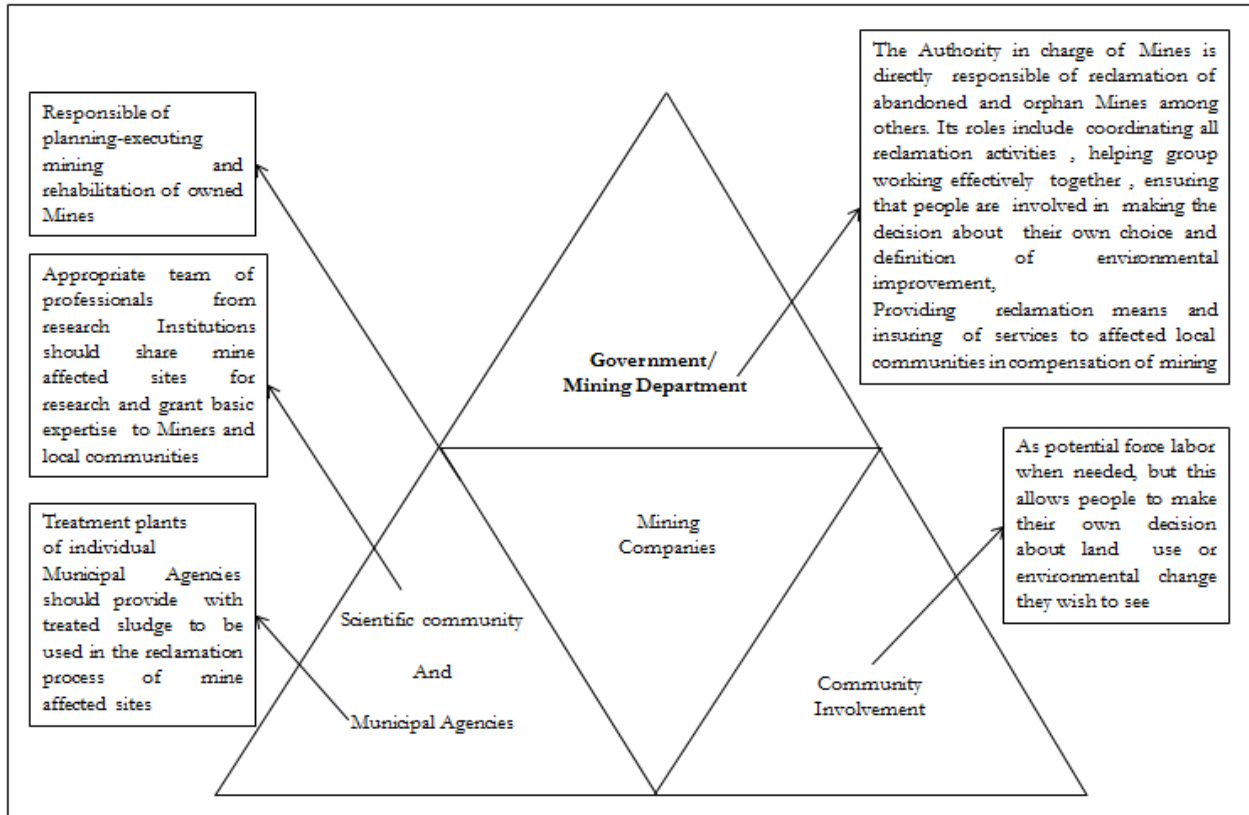
The study showed that mined sites are different because of their inherent physical environment and post mining usages. For this, each site must be evaluated and treated independently. Physical, chemical, and biological measurable parameters for controlling reclamation must be identified. Field evaluation is compulsory and must be supported by laboratory analyses. Because of the inherent site's specificity as already mentioned, parameters that limit successful reclamation are expected to be site specific and most must be evaluated on a case by case basis. Furthermore, adequate site survey and assessment are required in order to identify overriding factors for a successful reclamation.

To sustainably develop promising environmental solutions for the SSOM sector, further researches should focus on establishing sustainable land use systems in areas to be mined. In view of this, mitigation strategies could be placed within two integrated perspectives, (i) a broader one which consists of converting sustainably the sector into a small-scale responsible enterprise (Figure 72), and (ii) a specific perspective with focus on concrete geomorphic measures.



**Figure 71:** Requirements and aspects to be considered towards the sustainability of SM sector

A broader consideration could be possible (i) through a greater scientific community involvement and government support with harmonized collaboration with all stakeholders, (ii) by providing sustainable guidelines through legal requirements, technical and practical knowledge, and setting well organized structures and consistent plans e.g. post-mining land use plan. Because of the complexity of the nature and the pertinence of the task of mitigating impacts resulting from SSOM, involvement and well-coordinated collaboration of all stakeholders (Figure 73) is beneficial for providing varied and complementary skills necessary for the success of restoration. Viewed in the context that reclamation of mines requires a wide ranges of expertise, tasks should be rescheduled and allocated to appropriate individuals or organizations.



**Figure 72:** Rescheduling tasks to ease the reclamation exercise of SSOM affected sites

In the introduction it has been specified this research as a geographic study, in regards of a broad and exploratory broad approach. The thesis provides a useful and comprehensive background to anyone who is interested in research on geomorphic processes associated with SSOM in Rwanda and similar mining sector of the world. A number of geomorphic processes have been assessed mainly from a qualitative point of view. Further studies would probably contribute greatly not only to the understanding of SSOM as a potential anthropogenic factor of land degradation, but also to formulate adequate strategies for mitigating resulting impacts and to move the sector towards a more responsible enterprise. Viewed in this latter consideration, there is a broad consensus that marked environmental improvements could be achieved if assistance is provided to the minerals commission from local governmental bodies and academic units, industry-specific environmental management tools and strategies are designed and implemented, and concerted effort is made to prospect for deposits suitable for small-scale mining, a key to preventing unnecessary exploitation.



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## Appendix I: Glossary of definitions

### *Abandoned and owned mines*

Abandoned mines are alternatively termed ‘derelict’, ‘orphan’, ‘former’ or ‘legacy’ mines. The terms mean slightly different things in different jurisdictions (Unger et al., 2015). For example, orphan mines are those where the owner of the mine is unknown and untraceable, in contrast to abandoned mines which are “mines” where mining leases or titles no longer exist (Unger et al., 2015). Their existence makes it difficult for the sector to gain the credibility with regulators and the public (Sawatsky et al., 2000). Attribute that all sites have in common is inexistent or incomplete remediation. Reasons for such problems include inadequate regulatory requirements, insufficient funds set aside for remediation, or inadequate community engagement to agree upon and meet closure expectations (Unger et al., 2015). All forms of mining legacies might become by default the responsibility of governments and the community. Any mine concession whom operators are known and mining titles exist is referred to in this thesis as an owned mine.

### *Degradation*

Degradation term is used to describe processes which lead to the land under consideration, being no longer fit for a wide range of uses from natural systems to building sites. This may take the form of geotechnical instability resulting in subsidence or landslips, or as erosion by wind or rain (Harris, et al., 1998).

### *Tailings*

Tailings are defined as the waste materials generated by the grinding and processing of ores and other materials containing economically retrievable minerals (Hossner & Hons, 1992).

### *Soil erosion and soil degradation/ soil depletion* (Okoth, 2002)

Soil erosion reduces productivity through physical loss of topsoil, reduction in rooting depth, removal of plant nutrient and loss of water. Soil erosion is normally quantified as an amount of soil lost from a given area over a specific period of time and expressed in standardized units mostly in tonnes per hectare per year. The term ‘soil degradation’ implies decline in soil quality through deterioration of the physical, chemical and biological properties of the soil. Accelerated soil erosion is one of the process that lead to soil degradation. It may be caused by depletion through intensive land use such as mining. Soil depletion means soil quality loss or decline in soil fertility due to removal of nutrients by eluviation or cheluviation



by water passing through the soil profile. The soil depletion process is less drastic and can easily be remediated through cultural practices and by adding appropriate soil amendments such as manure and fertilizers.

### *Reclamation*

Within the mining context, reclamation often refers to the general process whereby the mined wasteland is returned to some forms of beneficial use (Harris et al., 1998; Cooke & Johnson, 2002), more specifically to making of land fit for cultivation (Li, 2006). According to Haigh (1995) land reclamation aims to replace an initially sterile by a productive soil. But whether this, or only some intermediate level of rehabilitation, can be achieved will depend on technique and circumstance (Bradshaw, 1997). This involves dealing with topography reshaping, construction soil design, among others (Craul & Rowe, 2008), because they are foundation for other subsequent action (Toy et al., 2002). Reclamation can best describe the restoration practice as the bulk of reclaimed lands are for agricultural production and forestry (Li, 2006).

### *Land Restoration*

Land restoration is the process by which an area is returned to its original state prior to degradation of any sort (Harris et al., 1998). Restoration is defined as a reinstatement of the pre-mining ecosystem in all its structural and functional aspects. However, the term has a broader meaning as a complex of operations which results in land being fully established once more in an acceptable environmental condition preferably for reversion to its original use or for a new use (Coppin & Box, 1998). In other words, restoration refers to restoring the land cover and use and land cover that existed before disturbance occur. The progression towards the reinstatement of the original ecosystem refers to as rehabilitation; whereas replacement is the creation of an alternative ecosystem to the original (Bradshaw, 1997), while acknowledging that the true replication might not be realistic (Hobbs & Norton, 1996).

### *Rehabilitation*

The term “rehabilitation” applies to areas which formerly had no growth at all, but with careful landscaping and fertilization works may be used to grow a limited number of species (Harris et al., 1998). Rehabilitation aims at putting the land impacted by the mining activity back to a sustainable usable condition (Nzimande & Chauke, 2012). It is the entire continuum of human actions performed in order to assist this recovery (Hobbs & Norton, 1996).

### *Re-cultivation*

Re-cultivation is the term often translated from other languages to mean the equivalent of reclamation, through implying the process of ground and soil preparation, vegetation establishment and management. Although evidence has indicated that the unassisted process of natural recovery of degraded land can be very powerful and deliver fully developed and functional ecosystems within 100 years (Bradshaw, 1997), this does not always occur, in particular, on the more adverse conditions of mine tailings dams and waste rocks. Restoration of mine wasteland often requires human assistance if the restoration goal is expected to be achieved within a reasonable timeframe (Li, 2006). Aftercare means the processes involved in managing the reclaimed/ restored/re-cultivated land to achieve a viable soil-plant system, including activities such as fertilizing, cutting/pruning, grazing, weed control and remedial or replacement work (Craul & Rowe, 2008).

Landscape restoration of closed mines may be regarded as applicable human involvement for remediating degraded landscapes caused by mining, thus enabling new land uses (Zhang et al., 2011). According to the literatures reported, landscape planning can bring ecological benefits but, as used for tourism effectively stimulate economic and social benefits, aiming at restoring the economic and recreational potential of given landscape. As the changes of the landscapes in mining processes also comply with the mining activities, leaving a new, particular but inherited landscape (Li, 2006), Specialists have suggested a planning theory that calls for inclusiveness, collaboration and ideal egalitarian, not only between natural ecosystems but also between natural and human ecosystems as well as within human ecosystems. Several researchers noticed however that it is hard to estimate the destruction of regional functions caused by mining activities (Zhang et al., 2011). For this reason, planning can be levelled for a recreation of specific habitat types on drastically disturbed land and progressively (Zhang et al., 2011). The closure of mine that integrates with natural, human, historical and cultural landscapes must be planned to ensure full use of existing landscape resources, maximization of ecological function improvement and sustainability of economic (Zhang et al., 2011). From a geomorphic perspective, the fundamental component to be considered first in the processes of rehabilitation of mine degraded lands is the topographic reconstruction, for the creation of steady-state landscapes (Toy, et al., 2002). They stress that “Other reclamation goals cannot be achieved if the surface experiences accelerated mass-movement and erosion rates”.

Land use is defined as specific uses or management-related activities, rather than the vegetation or cover of the land (Holmberg, 1983). Post-mining land use is considered as a change to an alternative land use which is subject to approval by the regulatory authority.

Municipal sludge is a solid, semisolid, or liquid muddy looking residue that results after plain old sewage (human and other waste from households and industries) is treated at a sewage plant. After being treated, the sewage sludge may be spread on non-organic agricultural land as a fertilizer or dust suppressant. The USDA notes that sewage sludge includes: "Domestic sceptage; scum or solids removed in primary, secondary, or advanced wastewater treatment processes; and a material derived from sewage sludge <http://organic.about.com>. Several researchers showed the beneficial of using municipal sludge for (i) reclamation of mine lands and as an amendment to stabilizing and re-vegetating areas near construction sites and roadways (Seaker & Sopper, 1988; Sopper, 1993).

Geomorphic processes associated with SSOM are regarded as spatial and temporal relocation of mine waste and soil, stream siltation, instability of surrounding of pits that sometimes involve mass movement. Our premise is that better understanding geomorphic process will guide towards a better development of mitigation measures.

#### *Mitigation*

The term refers to minimization of impacts associated with SSOM. As impact cannot be avoided, attenuating strategies should be presented with respect to the stabilization of the site and management of erosion processes along and or after mining operation.

Basic definitions relating to physical parameters of a watershed are given below (Umrikar et al., 2013):

#### *Form factor*

*Form factor:* It is the ratio between the basin area and the square of the basin length. Narrow and deep channels possess low form ratio whereas shallow, wide channels high form ratio.

#### *Basin shape factor*

*Basin shape factor:* It is the ratio of area of the basin to the square of the length of the basin.

#### *Basin shape factor*

*Basin shape factor:* For the outline form of watershed, a dimensionless circularity ratio as a quantitative method is used by geomorphologist and hydrologists (Strahler 1952). Circularity ratio is defined as the ratio of watershed area to the area of a circle having the same perimeter as the watershed and it is pretentious by the lithological character of the watershed.

#### *Elongation ratio*

*Elongation ratio* is defined as the diameter of a circle of the same area as the basin to the maximum basin length. The varying slopes of watershed can be classified with the help of the index of elongation ratio, i.e. circular (0.9-0.10), oval (0.8-0.9), less elongated (0.7-0.8), elongated (0.5-0.7), and more elongated (less than 0.5). Further values near to 1.0 are typical of regions of very low relief, whereas values in the range of 0.6 to 0.8 are associated with strong relief and steep ground slope.

*Compactness coefficient*

*Compactness coefficient:* Compactness ratio is defined as the ratio of the area of the basin to the perimeter of the basin.

## Appendix II: Additional data on tantalum mining and producers worldwide

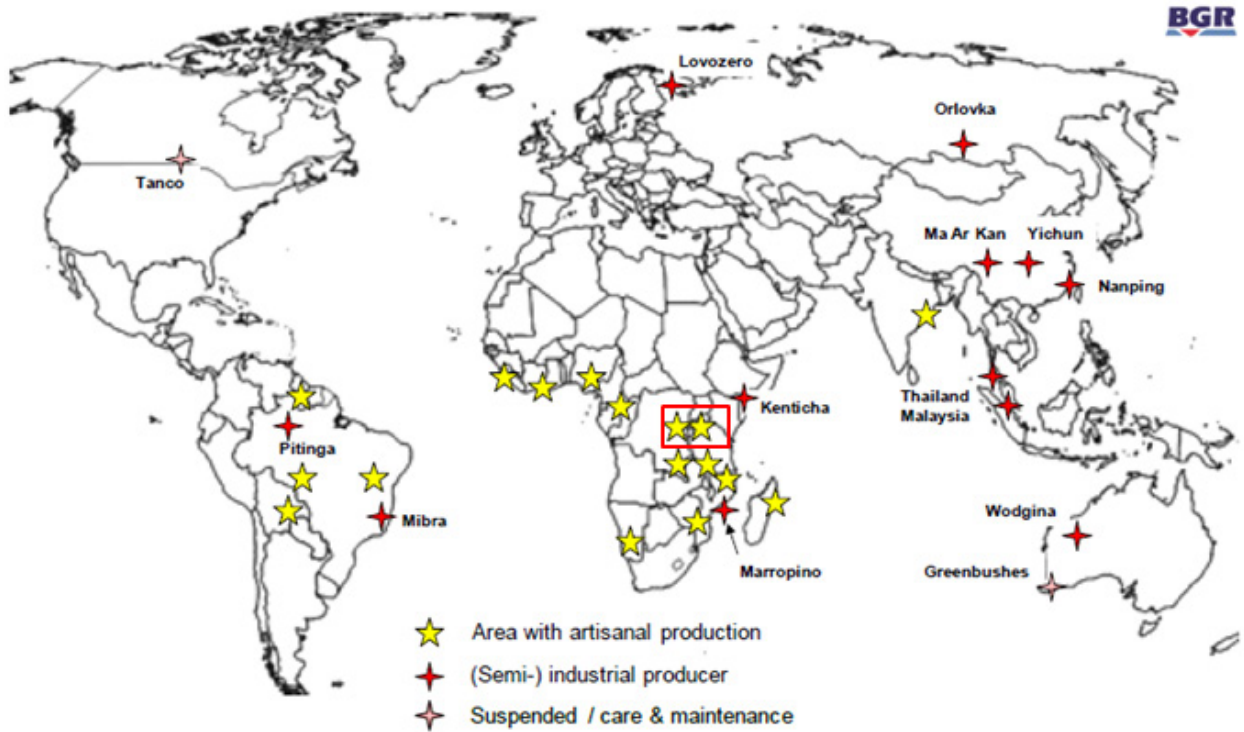


Figure 73: Global Distribution of tantalum producers (modified from Dorner et al., 2012)

## Appendix III: Slope classes of the Gatumba Watershed

Table 32: Distribution of slope class and corresponding area

Slope Class (°)	Total Area (ha)	Total Slope (%)
0-5	171,82	2,9
5 -15	1507,29	25,7
15 -35	4043,3	66,8
35-50	272,95	4,5
>50	9,69	0,1
Total	6004,9	100

## Appendix V: Infiltration rates against time

**Table 33:** Infiltration rate on the control site one

Cumulative time (min)	Water Intake (mm)	Infiltration rate (mmmin <sup>-1</sup> )	Infiltration rate (mmhr <sup>-1</sup> )	Accumulated Infiltration (mm)
0	0			
1	4,1	4,10	246,00	4,10
2	6,1	3,05	183,00	10,20
3	7,3	2,43	146,00	13,40
4	8,9	2,23	133,50	16,20
4	8,9	2,23	133,50	17,80
5	11	2,20	132,00	19,90
6	12,6	2,10	126,00	23,60
7	13,5	1,93	115,71	26,10
8	14,2	1,78	106,50	27,70
9	14,6	1,62	97,33	28,80
10	15,6	1,56	93,60	30,20
11	16,6	1,51	90,55	32,20
12	16,6	1,38	83,00	33,20
13	17,9	1,38	82,62	34,50
14	19,2	1,37	82,29	37,10
15	20,7	1,38	82,80	39,90
16	21,9	1,37	82,13	42,60
17	22,4	1,32	79,06	44,30
18	23,2	1,29	77,33	45,60
19	24,1	1,27	76,11	47,30
20	24,9	1,25	74,70	49,00
21	25,2	1,20	72,00	50,10
22	25,2	1,15	68,73	50,40
23	26,2	1,14	68,35	51,40
24	27,8	1,16	69,50	54,00
25	29,2	1,17	70,08	57,00
26	30,4	1,17	70,15	59,60
27	31,5	1,17	70,00	61,90
28	32,5	1,16	69,64	64,00
29	33,4	<b>1,15</b>	<b>69,10</b>	<b>65,90</b>

**Table 34:** Infiltration rate on the control site two

Cumulative time (min)	Water Intake (mm)	Infiltration rate (mmmin <sup>-1</sup> )	Infiltration rate (mmhr <sup>-1</sup> )	Accumulated Infiltration (mm)
0	0			
1	7,4	7,40	444,00	7,4
2	8,1	4,05	243,00	15,5
3	8,7	2,90	174,00	16,8
4	9,2	2,30	138,00	17,9
5	9,8	1,96	117,60	19
6	10,3	1,72	103,00	20,1
7	11	1,57	94,29	21,3
8	11,3	1,41	84,75	22,3
9	11,9	1,32	79,33	23,2
9	11,9	1,32	79,33	23,8
11	12,9	1,17	70,36	24,8
13	13,9	1,07	64,15	26,8
15	14,9	0,99	59,60	28,8
17	15,9	0,94	56,12	30,8
19	16,9	<b>0,89</b>	<b>53,37</b>	<b>32,8</b>

**Table 35:** Infiltration rate Ex-mine cultivated site one

Cumulative time (min)	Water Intake (mm)	Infiltration rate (mmmin <sup>-1</sup> )	Infiltration rate (mmhr <sup>-1</sup> )	Accumulated Infiltration (mm)
0	0			
1	2,1	2,10	126,00	2,1
2	3,1	1,55	93,00	5,2
3	3,6	1,20	72,00	6,7
4	4,7	1,18	70,50	8,3
4	4,7	1,18	70,50	9,4
6	5,6	0,93	56,00	10,3
8	7,3	0,91	54,75	12,9
10	9,0	0,90	54,00	16,3
10	9,0	0,90	54,00	18,0
12	9,9	0,83	49,50	18,9
14	11,5	0,82	49,29	21,4
16	13,2	<b>0,83</b>	<b>49,50</b>	<b>24,7</b>

**Table 36:** Infiltration rate on Ex-mine cultivated site two

Cumulative time (min)	Water Intake (mm)	Infiltration rate (mmmin <sup>-1</sup> )	Infiltration rate (mmhr <sup>-1</sup> )	Accumulated Infiltration (mm)
0	0			
1	0,6	0,60	36,00	0,6
2	1,1	0,55	33,00	1,7
3	1,6	0,53	32,00	2,7
4	2,2	0,55	33,00	3,8
5	2,7	0,54	32,40	4,9
6	3,2	0,53	32,00	5,9
7	3,8	0,54	32,57	7
8	4,3	<b>0,54</b>	<b>32,25</b>	<b>8,1</b>

**Table 37:** Infiltration rate on Ex-mine reclamation site one

Cumulative time (min)	Water Intake (mm)	Infiltration rate (mmmin <sup>-1</sup> )	Infiltration rate (mmhr <sup>-1</sup> )	Accumulated Infiltration (mm)
0	0			
5	1,0	0,20	12,00	1,0
10	1,9	0,19	11,40	2,9
15	2,3	0,15	9,20	4,2
20	3,0	0,15	9,00	5,3
25	3,4	0,14	8,16	6,4
30	3,9	0,13	7,80	7,3
35	4,4	0,13	7,54	8,3
40	4,9	<b>0,12</b>	<b>7,35</b>	<b>9,3</b>

**Table 38:** Infiltration rate on Ex-mine reclamation site two

Cumulative time (min)	Water Intake (mm)	Infiltration rate (mmmin <sup>-1</sup> )	Infiltration rate (mmhr <sup>-1</sup> )	Accumulated Infiltration (mm)
0	0			
1	0,3	0,30	18,00	0,3
2	0,4	0,20	12,00	0,7
3	0,6	0,20	12,00	1,0
4	0,8	0,20	12,00	1,4
5	1,0	0,20	12,00	1,8
6	1,1	0,18	11,00	2,1
7	1,2	0,17	10,29	2,3
8	1,3	0,16	9,75	2,5
9	1,4	0,16	9,33	2,7
10	1,5	0,15	9,00	2,9
11	1,6	<b>0,15</b>	<b>8,73</b>	<b>3,1</b>



**Table 39:** Infiltration rate onex-mine self-recovering site one

Cumulative time (min)	Water Intake (mm)	Infiltration rate (mm min <sup>-1</sup> )	Infiltration rate (mm hr <sup>-1</sup> )	Accumulated Infiltration (mm)
0	0			
5	0,7	0,14	8,40	0,7
10	1,0	0,10	6,00	1,7
15	1,4	0,09	5,60	2,4
20	1,7	0,09	5,10	3,1
25	2,1	0,08	5,04	3,8
30	2,4	0,08	4,80	4,5

**Table 40:** Infiltration rate enex-mine self-recovering site two

Cumulative time (min)	Water Intake (mm)	Infiltration rate (mm min <sup>-1</sup> )	Infiltration rate (mm hr <sup>-1</sup> )	Accumulated Infiltration (mm)
0	0			
1	2,1	2,10	126,00	2,1
2	4,1	2,05	123,00	6,2
3	7,1	2,37	142,00	11,2
4	8,9	2,23	133,50	16
4	8,9	2,23	133,50	17,8
5	11,5	2,30	138,00	20,4
6	13,6	2,27	136,00	25,1
7	15,6	2,23	133,71	29,2
8	17,3	2,16	129,75	32,9
8	17,3	2,16	129,75	34,6
9	18,9	2,10	126,00	36,2
10	20,8	2,08	124,80	39,7
11	22,9	2,08	124,91	43,7
12	24,4	2,03	122,00	47,3
13	26,6	2,05	122,77	51
13	26,6	2,05	122,77	53,2
14	27,9	1,99	119,57	54,5
15	29,4	1,96	117,60	57,3
16	31,2	1,95	117,00	60,6
17	32,6	1,92	115,06	63,8
18	33,9	1,88	113,00	66,5
19	35,2	1,85	111,16	69,1

**Table 41:** Infiltration rate categories per study site and soil texture dependency

Site	Clay (%)	Silt (%)	OM (%)	IR (mm hr <sup>-1</sup> )	Infiltration Category <sup>a</sup>	Soil Class	Textural
Control Site	18,60	22,20	1,11	69,10	Moderate		Sandy loam
	40,33	19,33	2,20	37,56	Moderate		Clay
	36,20	20,90	1,72	85,64	Moderately rapid		Clay loam
	45,95	18,63	2,22	28,55	Moderate		Clay
Ex_Mine cultivated Site	33,00	25,00	2,16	49,50	Moderate		Clay loam
	41,00	17,00	1,50	18,80	Moderately slow		Clay
	38,00	26,00	2,13	32,25	Moderate		Clay loam
	40,00	22,00	1,90	6,30	Slow		Clay loam
Ex_Mine Self_recovering Site	46,00	16,00	0,88	111,16	Rapid		Clay
	42,00	11,00	1,41	4,80	Very Slow		Clay loam
	36,00	19,00	0,97	7,40	Slow		Sandy clay loam
	38,00	16,00	1,11	5,60	Slow		Sandy Clay
Ex_Mine Reclamation Site	26,00	24,00	1,74	7,35	Slow		Sandy clay loam
	32,00	26,00	2,55	8,73	Slow		Clay loam
	50,00	16,00	3,28	11,40	Moderately slow		Clay
	44,00	19,00	3,03	3,80	Very Slow		Clay

<sup>a</sup>= After Bai (1979) (cited in Westerberg, 1999)

## Appendix VI: Additional data concerning C factor

Table 42: C Factor values for the Universal Soil Loss Equation (Morgan, 2005)

Practice	Average annual C Factor
Bare soil	1
Forest or dense shrub, high mulch crops	0,001
Savanna or prairie grass in good condition	0,01
overgrazed savanna or prairie grass	0,1
Maize, sorghum or millet, high productivity, conventional tillage	0,20-0,55
Maize, sorghum or millet, low productivity, conventional tillage	0,50-0,90
Maize, sorghum or millet, high productivity, chisel ploughing into residue	0,12-0,20
Maize, sorghum or millet, low productivity, chisel ploughing into residue	0,30-0,45
Maize, sorghum or millet, high productivity, no or minimum tillage	0,02-0,10
Cotton	0,40-0,70
Meadow grass	0,01-0,025
Soya beans	0,20-0,50
Wheat	0,10-0,40
Rice	0,10-0,20
Groundnuts	0,30-0,80
Palm trees, coffee, cocoa with cover crops	0,10-0,30
pineapple on contour; residue removed	0,10-0,40
pineapple on contour; with surface residue	0,01
Potatoes; rows downslope	0,20-0,50
Potatoes; rows across slope	0,10-0,40
Cowpeas	0,30-0,40
strawberries, with weed cover	0,27
pome granate, with weed cover	0,08
pome granate, clean-weeded	0,56
ethiopian tef	0,25
sugar cane	0,13-0,40
Yams	0,40-0,50
Pigeon peas	0,60-0,70
Mungbean	0,04
Chilli	0,33
Coffee: after first harvest	0,05
Plantains: after establishment	0,05-0,10
Papaya	0,21

## Appendix VII: Rainfall erosivity and erosivity coefficient

**Table 43:** Cross-validation of results of the estimated R-factor

Station	Estimated R Factor	Predicted R Factor	Error	Std Error	Stdd _Error	Norm Value	Station	Estimated R Factor	Predicted R Factor	Error	Std Error	Stdd _Error	Normal Value
1	232,88	304,31	71,43	65,29	1,09	1,32	47	340,41	359,52	19,11	27,92	0,68	0,79
2	505,48	527,05	21,57	43,48	0,50	0,46	48	404,11	510,94	106,83	65,25	1,64	1,77
3	394,86	562,10	167,24	62,75	2,67	2,54	49	352,74	335,77	-16,97	33,21	-0,51	-0,65
4	405,48	436,01	30,53	48,77	0,63	0,62	50	459,93	466,62	6,69	59,46	0,11	0,06
5	555,48	569,84	14,36	62,41	0,23	0,17	51	377,06	368,29	-8,77	34,12	-0,26	-0,28
6	438,36	414,95	-23,41	59,75	-0,39	-0,49	52	574,66	511,36	-63,30	65,98	-0,96	-1,09
7	479,45	470,63	-8,82	59,50	-0,15	-0,14	53	648,97	618,38	-30,59	47,34	-0,65	-0,83
8	465,07	476,06	10,99	64,36	0,17	0,14	54	543,15	414,87	-128,28	63,17	-2,03	-1,77
9	389,04	338,26	-50,78	39,65	-1,28	-1,26	55	344,52	347,58	3,06	45,25	0,07	0,00
10	393,15	327,00	-66,15	47,89	-1,38	-1,47	56	357,88	345,05	-12,83	64,43	-0,20	-0,22
11	314,38	356,95	42,57	54,92	0,78	0,87	57	372,95	454,14	81,19	63,97	1,27	1,47
12	592,81	528,82	-63,99	49,62	-1,29	-1,32	58	627,44	589,01	-38,43	48,95	-0,79	-1,00
13	563,75	538,26	-25,49	37,77	-0,67	-0,91	59	428,08	407,07	-21,01	41,26	-0,51	-0,62
14	430,82	374,99	-55,83	46,12	-1,21	-1,20	60	620,21	626,20	5,99	40,75	0,15	0,11
15	420,55	543,38	122,83	63,45	1,94	1,92	61	449,32	473,91	24,59	37,75	0,65	0,75
16	480,48	538,58	58,10	53,24	1,09	1,26	62	461,64	348,41	-113,23	63,83	-1,77	-1,65
17	664,04	588,46	-75,58	36,35	-2,08	-2,13	63	389,02	356,43	-32,59	63,23	-0,52	-0,68
18	366,09	454,83	88,74	63,14	1,41	1,65	64	481,51	520,64	39,13	61,34	0,64	0,68
19	387,33	434,13	46,80	62,04	0,75	0,83	65	378,08	375,88	-2,20	63,97	-0,03	-0,03
20	436,34	524,51	88,17	63,50	1,39	1,55	66	357,88	349,08	-8,80	28,22	-0,31	-0,40
21	475,07	458,07	-17,00	62,19	-0,27	-0,34	67	376,03	373,19	-2,84	7,42	-0,38	-0,46
22	485,96	542,84	56,88	61,41	0,93	1,04	68	373,63	374,82	1,19	3,58	0,33	0,25
23	251,37	400,32	148,95	66,85	2,23	2,13	69	373,63	372,54	-1,09	3,71	-0,29	-0,37
24	411,64	447,82	36,18	63,17	0,57	0,55	70	378,42	416,51	38,09	60,66	0,63	0,65
25	307,53	318,81	11,28	42,00	0,27	0,22	71	414,38	464,10	49,72	51,84	0,96	1,09
26	292,12	317,87	25,75	48,40	0,53	0,49	72	457,19	444,24	-12,95	52,79	-0,25	-0,25
27	362,67	356,91	-5,76	55,58	-0,10	-0,08	73	471,92	446,82	-25,10	37,53	-0,67	-0,87
28	717,47	447,98	-269,49	64,86	-4,16	-2,54	74	325,34	329,56	4,22	12,51	0,34	0,28
29	313,42	319,89	6,47	56,68	0,11	0,08	75	402,04	387,42	-14,62	40,59	-0,36	-0,43
30	446,92	509,31	62,39	57,89	1,08	1,20	76	344,86	340,16	-4,70	18,14	-0,26	-0,31
31	366,78	357,46	-9,32	61,91	-0,15	-0,17	77	345,21	316,90	-28,31	63,00	-0,45	-0,55
32	335,96	365,58	29,62	46,13	0,64	0,72	78	308,22	364,72	56,50	63,94	0,88	0,91
33	372,6	377,17	4,57	7,42	0,62	0,58	79	390,07	387,87	-2,20	43,90	-0,05	-0,06
34	433,56	403,45	-30,11	65,04	-0,46	-0,58	80	603,08	519,11	-83,97	64,06	-1,31	-1,39
35	398,29	463,76	65,47	52,76	1,24	1,39	81	491,15	445,25	-45,90	54,92	-0,84	-1,04
36	571,23	535,29	-35,94	63,62	-0,56	-0,72	82	480,48	447,12	-33,36	54,86	-0,61	-0,79
37	428,77	452,97	24,20	63,13	0,38	0,37	83	322,95	326,60	3,65	52,30	0,07	0,03
38	304,79	327,29	22,50	64,25	0,35	0,31	84	427,06	398,71	-28,35	64,09	-0,44	-0,52
39	322,62	329,30	6,68	16,02	0,42	0,40	85	569,86	447,89	-121,97	59,84	-2,04	-1,92
40	501,37	455,63	-45,74	59,31	-0,77	-0,95	86	688,73	639,22	-49,51	34,46	-1,44	-1,55
41	455,82	446,59	-9,23	62,63	-0,15	-0,11	87	375,01	432,85	57,84	64,99	0,89	0,95
42	376,03	337,57	-38,46	65,75	-0,58	-0,75	88	308,92	368,14	59,22	55,66	1,06	1,14
43	240,41	301,41	61,00	67,24	0,91	1,00	89	394,18	425,53	31,35	58,31	0,54	0,52
44	461,64	475,97	14,33	38,98	0,37	0,34	90	616,14	633,30	17,16	35,48	0,48	0,43
45	597,95	589,19	-8,76	47,56	-0,18	-0,19	91	538,71	473,07	-65,64	54,81	-1,20	-1,14
46	470,55	479,65	9,10	38,26	0,24	0,19	92	364,38	454,83	88,74	63,14	1,41	1,65

**Table 44:** Maximum and minimum rainfall erosivity and coefficient

Region	R Factor (MJ mm ha <sup>-1</sup> hr <sup>-1</sup> yr <sup>-1</sup> )			Erosivity coefficient
	Min	Max	Mean	
Country wide	236.087	711.983	474.035	3.02
Western Province	381.890	675.441	528.665	1.85
Northern Province	318.032	711.983	515.007	2.32
Southern Province	368.173	617	492.586	1.74
Gatumba Area	369.198	572.843	469.020	1.06
Ngororero District	374.983	534.247	454.615	1.42
Estern Province	236.087	518.788	377.437	1.97
Kigali	327.433	409.057	368.249	1.34

## Appendix VIII: Watershed parameters

**Table 45:** Physical parameters used to quantitatively define watershed geomorphology

Parameter	Definition	Formula	Value	Description
Form Factor	$FF = \frac{\text{watershed area}}{(\text{watershed length})^2}$	$\frac{A}{L^2}$	<1	The smaller values result in smaller peaks at outlet
Basin shape factor	$B_S = \frac{(\text{watershed length})^2}{\text{Watershed area}}$	$\frac{L^2}{A}$	>1	The smaller values result in bigger peaks at outlet
Elongation ratio	$R_e = \frac{\text{diameter or circle of watershed}}{\text{watershed length}}$	$\frac{1.128 A^{0.5}}{L}$	≤1	The smaller values result in smaller peaks at outlet
Circularity ratio	$R_C = \frac{\text{watershed area}}{\text{Area of circle of watershed perimeter}}$	$\frac{12.57A}{P_r^2}$	≤1	The smaller values result in smaller peaks at outlet
Compactness coefficient	$C_C = \frac{\text{watershed area}}{\text{Perimeter of circle of watershed area}}$	$\frac{0.2821P_r}{A^{0.5}}$	≥1	The smaller values result in bigger peaks at outlet

Note: A= watershed area, L= watershed length, and Pr = perimeter (Karamouz et al. 2013)

## Appendix IX: Soil Erosion Risks

**Table 46:** Actual Soil erosion rate (t ha<sup>-1</sup>yr<sup>-1</sup>)

Class	Area (ha)	Area (%)	Min	Max	Mean
1	3547.09	49.07	1	3	2
2	2116.73	35.52	4	15	9
3	307.45	15.12	16	45	26
4	15.01	0.25	46	123	67
5	1.80	0.03	124	309	184
6	0.60	0.01	-	765	>184
Average Soil Loss			16.75	46.5	27

**Table 47:** Maximum and minimum soil erosion rates with terracing and OM content

Slope (°)	Max > 2% OM	Max 2 % OM	Max 0,5 % OM	Mean 0,5 % OM	Mean 2 % OM	Mean > 2 % OM
0	1,25	1,01	1,07	0,06	0,05	0,05
1	4,57	5,37	6,20	0,19	0,16	0,14
2	9,43	11,15	12,87	0,37	0,32	0,28
3	10,81	12,77	14,73	0,48	0,41	0,37
4	19,11	22,58	26,06	0,53	0,46	0,42
5	25,39	30,00	34,62	0,60	0,52	0,48
6	30,34	35,84	41,38	0,63	0,54	0,49
7	31,81	27,61	31,87	0,68	0,59	0,54
8	55,72	65,83	75,99	0,75	0,65	0,60
9	63,06	74,50	86,00	0,78	0,68	0,63
10	64,37	76,10	87,77	0,79	0,69	0,64
11	124,49	147,07	169,76	0,94	0,82	0,76
12	109,14	129,03	148,82	1,09	0,95	0,89
13	134,14	158,48	182,92	1,09	0,94	0,87
14	163,21	192,82	222,56	1,13	0,98	0,92
15	106,82	87,88	91,56	1,21	1,03	0,96
16	121,21	98,16	103,89	1,25	1,07	0,99
17	198,01	234,11	270,01	1,41	1,21	1,13
18	166,27	143,53	94,47	1,52	1,31	1,21
19	90,11	72,98	77,23	1,57	1,34	1,24
20	152,56	158,54	182,99	1,72	1,48	1,36
21	207,44	179,08	193,17	1,78	1,53	1,40
22	146,95	173,61	200,39	1,89	1,62	1,49
23	93,88	75,98	80,47	2,00	1,72	1,58
24	63,50	55,35	51,49	2,11	1,82	1,67
25	91,12	73,74	78,11	2,25	1,94	1,78
26	146,05	118,28	125,18	2,38	2,05	1,89
27	128,26	103,80	109,94	2,63	2,27	2,10
28	89,79	78,30	63,05	2,75	2,38	2,20
29	142,75	130,57	122,36	2,88	2,49	2,30
30	150,21	137,39	128,75	2,92	2,53	2,34
31	102,18	89,11	79,31	3,04	2,63	2,44
32	63,76	57,13	48,37	3,16	2,73	2,53
33	102,32	91,70	77,63	3,18	2,74	2,54
34	70,22	62,92	53,27	3,23	2,79	2,58
35	73,10	65,51	55,46	3,31	2,86	2,65
36	113,83	102,69	94,40	3,35	2,88	2,68
37	54,20	47,41	41,78	3,38	2,92	2,70

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Slope(°)	Max > 2% OM	Max 2 % OM	Max 0,5 % OM	Mean 0,5 % OM	Mean 2 % OM	Mean > 2 % OM
38	120,31	104,90	84,47	3,48	3,02	2,82
39	38,10	33,32	30,92	3,47	3,01	2,78
40	29,98	27,94	32,25	3,58	3,10	2,87
41	38,82	33,96	29,93	3,53	3,05	2,86
42	88,54	79,34	67,17	3,49	3,03	2,81
43	33,60	39,70	45,82	3,54	3,10	2,87
44	39,87	47,10	54,37	3,52	3,12	2,94
45	20,28	22,77	26,28	3,28	2,86	2,66
46	99,09	88,79	75,17	3,82	3,33	2,99
47	23,91	25,99	29,99	3,66	3,24	3,00
48	23,19	23,60	27,24	3,77	3,35	3,11
49	43,50	38,98	33,00	3,92	3,46	3,12
50	43,35	38,85	32,88	4,27	3,80	3,49
51	32,26	38,11	43,99	3,82	3,43	3,12
52	46,69	40,71	44,13	4,28	3,90	3,51
53	26,73	23,95	20,28	3,81	3,33	2,88
54	28,79	23,30	24,68	3,52	3,14	2,78
55	25,47	20,61	21,83	3,34	2,90	2,58
56	15,81	18,68	21,55	3,52	3,35	3,15
57	12,20	14,41	16,63	3,03	2,84	2,53
58	10,75	12,48	14,41	3,26	3,15	3,01
59	11,75	9,53	11,00	2,68	2,35	2,05
60	12,64	10,23	10,83	2,57	2,15	1,70
61	8,31	9,82	11,33	4,19	4,10	4,03
62	9,92	11,72	13,52	2,46	2,33	2,30
63	14,89	17,59	20,31	6,18	5,68	5,66
64	1,59	1,43	1,21	0,71	0,99	1,12
66	10,44	12,33	14,23	11,68	10,12	8,57

**Table 48:** Maximum and minimum soil erosion rates with contours and OM content

Slope (°)	Max > 2% OM	Max 2 % OM	Max 0,5 % OM	Mean 0,5 % OM	Mean 2 % OM	Mean > 2 % OM
0	6,88	5,57	7,27	0,34	0,28	0,24
1	25,00	29,55	34,09	1,04	0,89	0,80
2	51,89	61,33	70,76	2,02	1,75	1,58
3	59,43	70,24	81,04	2,63	2,25	2,02
4	105,12	124,23	127,53	2,93	2,52	2,30
5	139,65	165,04	190,43	3,29	2,85	2,62
6	166,88	197,22	227,57	3,41	2,95	2,73
7	159,04	138,08	159,33	3,43	2,95	2,70
8	278,62	329,27	379,93	3,74	3,28	3,03
9	315,32	372,65	429,98	3,91	3,39	3,17
10	321,83	380,35	438,86	3,97	3,46	3,19
11	622,46	735,63	848,81	4,69	4,08	3,83
12	545,68	644,89	744,10	5,46	4,76	4,46
13	670,71	792,66	914,61	5,44	4,72	4,39
14	816,07	964,45	1112,82	5,66	4,89	4,58
15	534,10	439,19	457,80	6,04	5,18	4,80
16	606,04	490,60	443,89	6,26	5,35	4,98
17	990,05	1170,06	1350,07	7,03	6,05	5,66
18	831,34	717,98	472,35	7,62	6,55	6,04
19	450,53	364,71	386,16	7,84	6,72	6,17
20	762,81	792,96	914,96	8,62	7,40	6,83
21	1037,21	895,77	965,85	8,91	7,65	7,02
22	734,75	868,34	1001,93	9,45	8,12	7,45
23	469,41	380,00	402,35	9,98	8,58	7,88
24	317,51	276,86	257,45	10,56	9,09	8,35
25	455,62	368,83	272,66	11,25	9,69	8,84
26	730,23	591,14	625,91	11,89	10,26	9,43
27	641,32	519,16	549,70	13,16	11,36	10,49
28	448,97	391,65	360,72	13,77	11,89	10,98
29	713,75	652,57	611,79	14,38	12,47	11,50
30	751,04	686,66	643,74	14,61	12,63	11,66
31	510,90	445,68	396,55	15,21	13,14	12,18
32	318,78	285,81	241,84	15,79	13,63	12,65
33	511,62	458,69	388,13	15,92	13,70	12,69
34	351,10	314,78	266,35	16,15	13,93	12,82
35	365,52	327,71	277,29	16,57	14,30	13,26
36	569,17	513,64	471,99	16,76	14,41	13,38
37	271,02	237,14	285,17	16,89	14,59	13,61
38	601,54	524,75	422,36	17,41	15,08	14,04

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Slope (°)	Max > 2% OM	Max 2 % OM	Max 0,5 % OM	Mean 0,5 % OM	Mean 2 % OM	Mean > 2 % OM
39	190,49	166,68	154,60	17,33	15,04	13,96
40	149,91	139,76	161,26	17,88	15,50	14,50
41	194,11	169,85	280,19	17,65	15,25	14,55
42	442,69	396,89	169,25	17,44	15,14	14,00
43	168,01	198,56	229,11	17,68	15,49	14,56
44	199,34	235,59	210,82	17,62	15,62	14,41
45	101,42	113,89	222,40	16,41	14,31	13,58
46	495,46	444,20	120,12	19,11	16,68	14,57
47	119,54	129,97	149,97	18,31	16,20	14,61
48	115,93	118,03	136,19	18,84	16,73	14,83
49	217,50	195,00	165,00	19,61	17,31	15,81
50	216,74	194,31	164,42	21,37	18,99	17,63
51	161,30	190,63	219,95	19,11	17,15	15,82
52	233,44	203,64	163,91	21,41	19,52	15,15
53	133,63	119,81	101,38	19,03	16,64	14,26
54	143,96	116,54	123,40	17,61	15,73	13,93
55	127,35	103,10	61,21	16,70	14,51	11,94
56	79,03	93,40	107,77	17,58	16,74	14,79
57	60,99	72,08	83,17	15,14	14,20	13,27
58	53,77	62,44	72,04	16,32	15,76	14,06
59	58,77	47,66	54,99	13,40	11,77	10,57
60	63,18	51,14	54,15	12,86	10,77	9,03
61	41,55	49,10	56,66	20,94	20,49	20,16
62	49,58	58,60	67,61	12,30	11,65	11,50
63	74,45	87,99	101,53	30,88	28,40	28,31
64	7,96	7,14	6,04	3,57	4,93	5,62
66	52,18	61,67	71,15	58,41	50,62	42,83

**Table 49:** Maximum and minimum soil erosion rates with striping and OM content

Slope (°)	Max > 2% OM	Max 2 % OM	Max 0,5 % OM	Mean 0,5 % OM	Mean 2 % OM	Mean > 2 % OM
0	2,68	3,09	3,57	0,16	0,14	0,12
1	12,27	14,51	16,74	0,51	0,44	0,39
2	25,47	30,11	34,74	1,00	0,87	0,78
3	29,18	34,48	39,78	1,30	1,11	0,99
4	45,91	54,26	62,61	1,44	1,24	1,13
5	68,55	81,02	93,48	1,63	1,41	1,29
6	81,92	96,82	111,71	1,70	1,47	1,34
7	79,52	69,04	79,66	1,72	1,48	1,35
8	139,31	164,64	189,97	1,87	1,64	1,51
9	157,66	186,32	214,99	1,96	1,70	1,58
10	160,92	190,17	219,43	1,98	1,73	1,60
11	311,23	367,82	424,40	2,36	2,06	1,92
12	272,84	322,44	372,05	2,74	2,39	2,23
13	335,36	396,33	457,31	2,73	2,37	2,19
14	408,04	482,22	556,41	2,83	2,45	2,29
15	267,05	219,60	228,90	3,02	2,59	2,40
16	258,94	236,74	221,95	3,14	2,68	2,49
17	495,03	585,03	675,03	3,51	3,02	2,83
18	415,67	358,99	236,18	3,81	3,27	3,02
19	225,26	182,36	193,08	3,91	3,35	3,08
20	499,02	430,97	457,48	4,33	3,72	3,41
21	518,60	447,88	482,92	4,46	3,83	3,51
22	367,37	434,17	500,96	4,73	4,07	3,72
23	234,71	190,00	201,18	4,99	4,29	3,94
24	158,75	138,43	128,73	5,28	4,54	4,17
25	194,17	169,38	136,33	5,61	4,83	4,42
26	365,12	295,57	312,96	5,95	5,13	4,71
27	320,66	259,58	274,85	6,58	5,68	5,25
28	224,48	196,27	180,36	6,89	5,95	5,49
29	356,88	326,29	305,89	7,19	6,23	5,75
30	375,52	343,33	321,87	7,30	6,31	5,83
31	255,45	222,84	198,27	7,60	6,57	6,09
32	159,39	142,90	120,92	7,90	6,81	6,32
33	255,81	229,35	194,06	7,95	6,84	6,34
34	175,55	157,39	133,18	8,05	6,94	6,41
35	182,76	163,86	138,65	8,28	7,15	6,63
36	284,58	256,82	236,00	8,38	7,21	6,69
37	135,51	123,57	142,58	8,48	7,34	6,81
38	300,77	262,38	211,18	8,70	7,52	7,02
39	95,24	83,34	77,30	8,70	7,54	6,98

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Slope (°)	Max > 2% OM	Max 2 % OM	Max 0,5 % OM	Mean 0,5 % OM	Mean 2 % OM	Mean > 2 % OM
40	74,96	69,88	80,63	8,99	7,79	7,25
41	102,74	121,42	140,10	8,90	7,72	7,27
42	112,94	99,22	84,63	8,67	7,52	7,00
43	84,01	99,28	114,56	8,93	7,82	7,28
44	77,30	91,36	105,41	8,73	7,72	7,21
45	81,55	96,37	111,20	8,31	7,28	6,79
46	136,68	119,59	60,06	9,40	8,16	7,29
47	59,77	64,99	74,98	9,03	7,96	7,31
48	57,96	59,01	68,09	9,16	8,09	7,42
49	108,75	97,50	82,50	9,89	8,73	7,90
50	108,37	97,16	82,21	10,69	9,50	8,81
51	80,65	95,31	109,98	9,70	8,66	7,91
52	116,72	101,82	81,95	9,92	8,76	7,58
53	66,82	59,90	50,69	9,46	8,29	7,13
54	71,98	58,27	61,70	8,81	7,85	6,96
55	25,45	26,52	30,60	7,71	6,76	5,97
56	39,52	46,70	53,89	8,37	8,01	7,39
57	30,50	36,04	41,58	7,83	7,39	6,64
58	26,89	31,22	36,02	7,70	7,53	7,03
59	29,39	23,83	27,50	6,91	6,07	5,28
60	31,59	25,57	27,08	6,78	5,67	4,52
61	20,77	24,55	28,33	10,47	10,25	10,08
62	24,79	29,30	33,81	6,15	5,82	5,75
63	37,23	43,99	50,76	15,44	14,20	14,15
64	3,98	3,57	3,02	1,78	2,47	2,81
66	26,09	30,83	35,58	29,21	25,31	21,42

**Table 50:** Average soil erosion rates

Slope (°)	Max > 2% OM	Max 2 % OM	Max 0,5 % OM	Mean 0,5 % OM	Mean 2 % OM	Mean > 2 % OM
0	3,61	3,23	3,97	0,19	0,16	0,14
1	13,95	16,48	19,01	0,58	0,50	0,44
2	28,93	34,19	39,46	1,13	0,98	0,88
3	33,14	39,16	45,19	1,47	1,26	1,13
4	56,72	67,02	72,07	1,63	1,41	1,28
5	77,86	92,02	106,18	1,84	1,59	1,46
6	93,05	109,96	126,89	1,91	1,65	1,52
7	90,12	78,24	90,28	1,95	1,67	1,53
8	157,88	186,58	215,29	2,12	1,86	1,71
9	178,68	211,16	243,66	2,22	1,92	1,80
10	182,37	215,54	248,69	2,25	1,96	1,81
11	352,73	416,84	480,99	2,66	2,32	2,17
12	309,22	365,46	421,66	3,10	2,70	2,53
13	380,07	449,16	518,28	3,09	2,68	2,48
14	462,44	546,50	630,60	3,21	2,77	2,60
15	302,66	248,89	259,42	3,42	2,93	2,72
16	328,73	275,17	256,58	3,55	3,03	2,82
17	561,03	663,07	765,04	3,98	3,43	3,21
18	471,09	406,83	267,67	4,32	3,71	3,42
19	255,30	206,68	218,83	4,44	3,81	3,50
20	471,46	460,82	518,48	4,89	4,20	3,87
21	587,75	507,58	547,31	5,05	4,34	3,98
22	416,36	492,04	567,76	5,36	4,60	4,22
23	266,00	215,33	228,00	5,66	4,86	4,47
24	179,92	156,88	145,89	5,99	5,15	4,73
25	246,97	203,99	162,37	6,37	5,49	5,01
26	413,80	335,00	354,68	6,74	5,81	5,34
27	363,41	294,18	311,50	7,46	6,44	5,95
28	254,42	222,08	201,37	7,80	6,74	6,22
29	404,46	369,81	346,68	8,15	7,06	6,52
30	425,59	389,13	364,79	8,28	7,16	6,61
31	289,51	252,54	224,71	8,62	7,45	6,90
32	180,64	161,95	137,04	8,95	7,72	7,17
33	289,92	259,91	219,94	9,01	7,76	7,19
34	198,96	178,36	150,93	9,14	7,88	7,27
35	207,13	185,69	157,13	9,39	8,10	7,52
36	322,53	291,05	267,46	9,50	8,17	7,58
37	153,58	136,04	156,51	9,58	8,28	7,70
38	340,87	297,34	239,34	9,86	8,54	7,96
39	107,94	94,45	87,61	9,83	8,53	7,91

Continued on next page

Slope (°)	Max > 2% OM	Max 2 % OM	Max 0,5 % OM	Mean 0,5 % OM	Mean 2 % OM	Mean > 2 % OM
40	84,95	79,20	91,38	10,15	8,80	8,21
41	111,89	108,41	150,07	10,02	8,67	8,23
42	214,72	191,82	107,02	9,87	8,56	7,94
43	95,21	112,51	129,83	10,05	8,80	8,24
44	105,50	124,68	123,53	9,96	8,82	8,19
45	67,75	77,68	119,96	9,33	8,15	7,68
46	243,74	217,53	85,12	10,78	9,39	8,28
47	67,74	73,65	84,98	10,33	9,13	8,31
48	65,69	66,88	77,17	10,59	9,39	8,45
49	123,25	110,49	93,50	11,14	9,83	8,94
50	122,82	110,11	93,17	12,11	10,76	9,98
51	91,40	108,02	124,64	10,88	9,75	8,95
52	132,28	115,39	96,66	11,87	10,72	8,75
53	75,72	67,89	57,45	10,77	9,42	8,09
54	81,58	66,04	69,93	9,98	8,91	7,89
55	59,43	50,08	37,88	9,25	8,06	6,83
56	44,79	52,93	61,07	9,82	9,36	8,44
57	34,56	40,84	47,13	8,67	8,14	7,48
58	30,47	35,38	40,83	9,09	8,82	8,04
59	33,31	27,01	31,16	7,66	6,73	5,97
60	35,80	28,98	30,69	7,40	6,20	5,08
61	23,54	27,82	32,11	11,86	11,61	11,43
62	28,10	33,20	38,31	6,97	6,60	6,52
63	42,19	49,86	57,53	17,50	16,09	16,04
64	4,51	4,04	3,42	2,02	2,80	3,18
66	29,57	34,94	40,32	33,10	28,69	24,27

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