Geomorphic thresholds and the characteristics of Vetiver grass in a mined landscape in eastern Pretoria - South Africa

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DECLARATION

I declare that this thesis is my own work. It is being submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the Degree of Master of Science at the School of Geography, Archaeology & Environmental Studies. It has not been submitted before for any other degree or examination at any other University.

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ABSTRACT

The use of Vetiver grass (*Vetiveria zizanioides*), namely the Vetiver System (VS) for mine tailing slope stabilization and erosion control is common practice. It is therefore important to understand the anthropogenic topographical signatures which affect the application of VS for revegetation of landscapes with mine tailings and hillslopes. This research focused on the assessment of slope features in order to understand their influence on VS application at a diamond mine located in the Cullinan area, Pretoria-East, South Africa. The specific objectives were to (i) assess a fusion approach to deriving Digital Elevation Model (DEM) data and then generate some derivates of slope including steepness, curvatures and surface exposure indices; and (ii) assess capacity of high-resolution remote sensing data for estimation of above ground vegetation cover on mine tailings and hill-slopes under to the Vetiver system. The data processing followed analytical capabilities in Geographic Information Systems (GIS). Results show that SPOT-6 derived NDVI was effective in predicting above ground vegetation cover (%) with an R^2 of 0.72 and a Root Mean Square Error (RMSE) of 8.87%. The assessment of topographic influences on VS application for revegetation highlighted the significant contribution of data fusion within GIS. This enables derivation of accurate DEM for characterizing slope features and vegetation cover in the study area. This research can be used as a basis for future work (i) evaluating data fusion techniques for generation of accurate DEM; and (ii) assessing topographic influences on VS in revegetation, erosion control, or soil remediation activities. The methodological approaches in this research affirm the capabilities of GIS and remote sensing techniques for generating accurate but low-cost data which eliminates the need for extensive fieldwork. Overall, this research should be of interest to environmental experts planning erosion control interventions in anthropogenic topographical landscapes with mine tailing signatures.

DEDICATION

In memory of my Mother! Rosemary Kafula Bwali

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CONTENTS

DECLARATION i
ABSTRACT ii
DEDICATION iii
ACKNOWLEDGEMENTS iv
CONTENTS v
LIST OF FIGURES and Tables viii
LIST OF ABBREVIATIONS AND ACRONYMS x

CHAPTER 1: INTRODUCTION 1

1.1. BACKGROUND 1
1.2. PROBLEM STATEMENT 3
1.3. OBJECTIVES 5
1.4. THE STUDY AREA 5
1.4.1. Locality 5
1.4.2. Climate 7
1.4.3. Geology and hydrology 7
1.4.4. Vegetation 8
1.4.5. Mine site rehabilitation 8
1.5. OUTLINE OF THE THESIS 9

CHAPTER 2: LITERATURE REVIEW 10

2.1. INTRODUCTION 10
2.1.1. Detachment 10
2.1.2. Entrainment 11
2.1.3. Erosion processes 13
2.2. TYPES OF EROSION 13
2.2.1. Sheet erosion 13
2.2.2. Rill erosion 13
2.2.3. Gully erosion 14
2.2.4. Channel erosion 15
2.3. FACTORS AFFECTING EROSION 16
2.3.1. Climate 16
2.3.2. Types of materials and their characteristics 16
2.3.3. Topography 17

2.3.4. Ground cover ... *17*

2.4. Erosion models ... 18

2.5. Erosion of tailing slopes ... 19

2.5.1. Soil erosion and erosion prevention ... *19*

2.5.2. Gullies on slopes of tailings dams ... *19*

2.5.3. Rehabilitation of tailings dams ... *20*

2.6. The Vetiver System ... 20

2.6.1. Introduction ... *20*

2.6.2. Morphological characteristics of Vetiver grass ... *23*

2.6.3. Physiological characteristics of vetiver grass ... *24*

2.6.4. History of Vetiver grass ... *25*

2.6.5. Vegetation and biotechnical erosion prevention ... *26*

2.7. Relevant case studies ... 27

2.7.1. Australia ... *27*

2.7.1. South Africa ... *27*

2.8. Remote methods and topographic measurements ... 29

2.8.1. Fusion techniques and digital elevation models ... *30*

2.8.2. Optical remote sensing and estimation of vegetation cover ... *32*

CHAPTER 3: RESEARCH METHODS AND MATERIALS ... 35

3.1. DEMs and fusion analysis ... 35

3.1.1. DEM data preparation ... *35*

3.1.2. Fusion of DEMs ... *37*

3.2. Derivation of topographic Variables ... 39

3.2.1. Elevation, slope and aspect transformation ... *39*

3.2.2. Site exposure index ... *40*

3.2.3. Surface curvatures ... *40*

3.3. Remotely sensed data analysis ... 41

3.3.1. SPOT-6 data acquisition and pre-processing ... *41*

3.3.2. Field materials and preparation of SPOT-6 imagery ... *43*

3.3.3. Normalized Difference Vegetation Index (NDVI) ... *44*

3.3.4. Image fusion ... *45*

3.4. Model validation and accuracy assessment ... 46

CHAPTER 4: RESULTS ... 48

4.1. VISUAL INTERPRETATION AND ACCURACY OF GENERATED DEM 48
4.2. DERIVATES OF SLOPE 51
4.2.1. Slope classification 51
4.2.2. Second derivates of slope and erosion 52
4.3. ABOVE GROUND VEGETATION CANOPY ESTIMATION 54
4.4. ABOVE-GROUND VEGETATION COVER AND TOPOGRAPHIC VARIABLES 56
CHAPTER 5: DISCUSSION AND CONCLUSIONS 58
5.1. DEM FUSION AND SLOPE DERIVATES 58
5.2. VEGETATION COVER AND TOPOGRAPHY 60
5.3. THRESHOLDING OF SLOPE AND THE VETIVER SYSTEM 61
5.4. CONCLUSIONS AND RECOMMENDATIONS 62
REFERENCES 63
APPENDICES 72
Appendix 1 72

LIST OF FIGURES AND TABLES

Figure 1.1 Study area showing mine tailings on SPOT-6 image (15-04-2018)....... 6
Figure 1.2 Visual representation of some eroding tailings at the Cullinan mine site. 9
Figure 2.1 The relationships between particle size and erosion potential, transportation or deposited of particles at different current velocities (Source: https://opentextbc.ca/geology/chapter/13-3-stream-erosion-and-deposition/)...... 12
Figure 2.2 Examples of erosion on diamond mine tailings with Kimberlite material and land surface erosion (Photos: Copyright of Diamcor Mining Inc., http://www.diamcormining.com). 15
Figure 3.1 Shaded relief (Hillshade raster) of the SRTM DEM (panel A) and cdDEM-5m (panel B), respectively. 36
Figure 3.2 Workflow of the DEMs fusion algorithm: algorithm adapted after Karkee et al (2008). 38
Figure 3.3 Showing the SPOT-6 spectral bands (grey-colour bars) against the spectral profile of different vegetation canopy types. 43
Figure 3.4 Pan-sharpened SPOT-6 (1.5 m) image (Right panels: Non-fused) with an improved resolution image compared with 6m–multispectral image (Left-hand panels) for better interpretation of tailings erosion highlighted in red oval shapes. 46
Figure 4.1 Input DEMs: SRTM (A) and cdDEM-5m (B) and final output fused DEM. 50
Figure 4.2Slope classification map 51
Figure 4.3 Map of site exposure index. 52
Figure 4.4 Profile curvature and above ground vegetation canopy survey locations. 53
Figure 4.5 Platform slope curvature and above ground vegetation canopy survey locations. 53
Figure 4.6 Standard slope curvature and above ground vegetation canopy survey locations. 54
Figure 4.7 The SPOT-6 derived NDVI image (A) and above ground vegetation canopy cover (B) 55

Figure 4.8 Predictive capacity of NDVI (Panel A) and observed vs predicted above-ground canopy cover (Panel B). 56
Figure 4.9 Relationship between topographic elements and vegetation. 57
Table 4.1 Descriptive statistics of input data and derived variables 57

LIST OF ABBREVIATIONS AND ACRONYMS

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CD	Chief Directorate
DEM	Digital Elevation Model
EVI	Enhanced Vegetation Index
GDEL	Global Digital Elevation Model
GIS	Geographical Information System
GPS	Global Positioning System
LAI	Leaf Area Index
LP DAAC	Land Processes Distributed Active Archive Center
NDVI	Normalized Difference Vegetation Index
NGI	National Geospatial Information
Ph	Potential Hydrogen
RUSLE	Revised Universal Soil Loss Equation
SANSA	South African National Space Agency
SAR	Synthetic Aperture Radar
SEI	Site Exposure Index
SRTM	Shuttle Radar Topography Mission
TVNI	The Vetiver Network International
USLE	Universal Soil Loss Equation
VS	Vetiver System

CHAPTER 1: INTRODUCTION

1.1. Background

Anthropogenic topographical signatures due to mine tailings can modify the geomorphology of landscapes and make such landscapes susceptible to erosion (Tarolli & Giulia, 2016). Erosion of tailings is a process in which soil and harmful mineral particles are removed and transported over long distances. Tailing materials are known to have little cohesion in the, often, silt grained particles. The deposition of mine tailings are usually without cover and therefore are exposed to the erosive power of rainfall and stormy winds over prolong periods of time. The removal and transportation of materials can also be caused by the combined effect of gravity and slope of mine tailings. In that regard, unprotected tailings material can be separated and dislodged easily to transport harmful soil particles downstream. Moreover, natural phenomena such as rainfall and stormy winds promote or accelerate erosion in landscape with anthropogenic topographical signatures (Ashmole & Motloung, 2008).

Erosion of tailings has significant impacts on the surrounding environment and can negatively affect the wellbeing of both fauna and flora. Concerns about environmental degradation due to mining activities have, therefore, led to the development of several geotextiles and mechanical remediation techniques to prevent or stabilize mine tailing slopes or slime dams (Castillo & Pintor, 2010). However, the use of mechanical methods alone for long-term rehabilitation programs can be expensive and unsustainable (Truong & Baker, 1998). At times, it is impossible to carry out mechanical remediation because mine tailings are composed of an unconsolidated material that is often contaminated with heavy metals that interact with cover materials. The major challenge is that it is when waste materials on mine tailings are not prevented from moving downslope, it often results in off-site contamination. For example, wind power and run-off rainwater and leaching can transport heavy metals that constitute off-site land contamination (Wahsha, et al., 2012). For that reason, practically effective and economical methods of erosion control programs are necessary for a long-term and sustainable rehabilitation of mine infrastructure and surrounding landscapes.

Besides geotextiles and mechanical methods of mine site rehabilitation, is the implementation of vegetation methods as a bioengineering tool for erosion control and slope stabilization (Castillo & Pintor, 2010). However, when revegetating mine landscape, toxic tailings with high levels of heavy metals is often challenging due to unfavourable environmental conditions (Castillo & Pintor, 2010). In that regard, it is important to investigate and identify vegetation species with specific traits that make them resilient to heavy metals in disposed mine wastes. Moreover, vegetation cover type or composition on a given topography can be characterized according to the steepness, width, length or the orientation of the slope, in addition to other environmental factors.

Based on its morphological and physiological traits, the Vetiver grass (*Vetiveria zizanioides*), namely the Vetiver System (VS), is known to be useful in water conservation, soil erosion and sediment control in agricultural systems (Greenfield, 1989). Traits of the vetiver grass make it effective for soil reinforcement and slope stability and interaction with harmful mine effluents. The VS is reported to be resilient to unfavourable soil and edaphic conditions such as toxic or heavy metal contaminations (Truong & Baker, 1998). In recent decades, VS has been extended to the field of environmental or ecological protection, particularly in the field of disused mine tailings rehabilitation programs. A great deal of scientific research from Australia, Asia, South America and Africa has shown that VS is an effective bioengineering tool for sustainable implementation of mine site rehabilitation, particularly for slope stabilization, soil and effluent remediation (Truong & Loch, 2004; Truong & Hart, 2001; Danh, et al., 2009). There is an increasing trend in the use of VS in South Africa, for erosion control and mined site rehabilitation (Truong, 2000). Whereas previous studies have reported that the VS is effective for controlling surface erosion and stabilizing slopes, the topographic thresholds of VS in establishing vegetation cover are not explicitly understood.

1.2. Problem statement

Besides the significant economic contributions of mining to economies, mining activities often produce large volumes of toxic wastes such as rock piles or tailings that cause geophysical and environmental disturbances. Evidence from the published literature shows that mining activities are a major contributor to landscape pollution (Ashmole & Motloung, 2008). In particular, mine tailings are composed mainly of fine grain, unconsolidated materials, that can be transported over long distances by erosion agents such as water, wind or the combined forces of gravity and slope. Methods used in the rehabilitation of mined landscapes have been to treat the contaminants chemically, mechanically restore the land or the use of bioengineering approaches. However, these methods are all expensive and at times impossible to carry out, due to some geophysical limitations at a mine site. In particular, the use of vegetation as a bioengineering tool requires that its application meets some landscape geomorphic thresholds (Hancock & Evans, 2006). For example, erosion of natural landscapes by gully incision can be considered a threshold function inversely dependent on the area of the drainage network, with slope identified as a prognostic tool for locating gully incision point and development (Istanbulluoglu & Bras, 2005). A simple approach to investigating the location of colluvial gully erosion and bioengineering control is by the area-slope relationship analysis method (Van Zyl, 2007). However, several studies that modelled erosion features mostly focus on ephemeral gullies in natural landscapes such as agricultural systems (Le Roux, et al., 2007). As a result, many of the erosion hazard modelling studies in non-agricultural systems have produced inconsistent results. Such inconsistency around mapping erosion in non-agricultural systems provides the opportunity for the current research to focus on investigating the topographic thresholds of VS for the establishment of vegetation cover on mine tailings and nearby hill slopes around the Cullinan mine in Pretoria–East, South Africa.

1.3. Objectives

The specific research objectives were to:

i) implement a data fusion approach for generating Digital Elevation Model (DEM) and derive derivates of slope (i.e., steepness, curvatures, and surface exposure index);

ii) estimate above-ground vegetation cover (%) by integrating remote sensing based vegetation index (i.e. NDVI) and field survey data;

iii) assess the influence of slope features on revegetation of tailings and hillslopes subjected to Vetiver System.

1.4. The study area

1.4.1. Locality

This research identified the Cullinan mine in the Pretoria East area, South Africa (Figure 1.1). Established in 1903, the Cullinan Diamond mine is one of the major sources of blue diamond in the world. The largest gem of blue diamond discovered at Cullinan mine in 1905 was 3,106.75 crats. The mine was named after Sir Thomas Cullinan. The mine is located approximately 40km east of Pretoria and is well-known as premier Diamond. The Mine lies on the Magaliesberg Range which has a geological history of deposited sediment of billions of years old. The most dominant geology is quartzites, shales, chert, and dolomite. These are deposited sediments of fractured and igneous intrusions of dolomite which is dominant soil type.

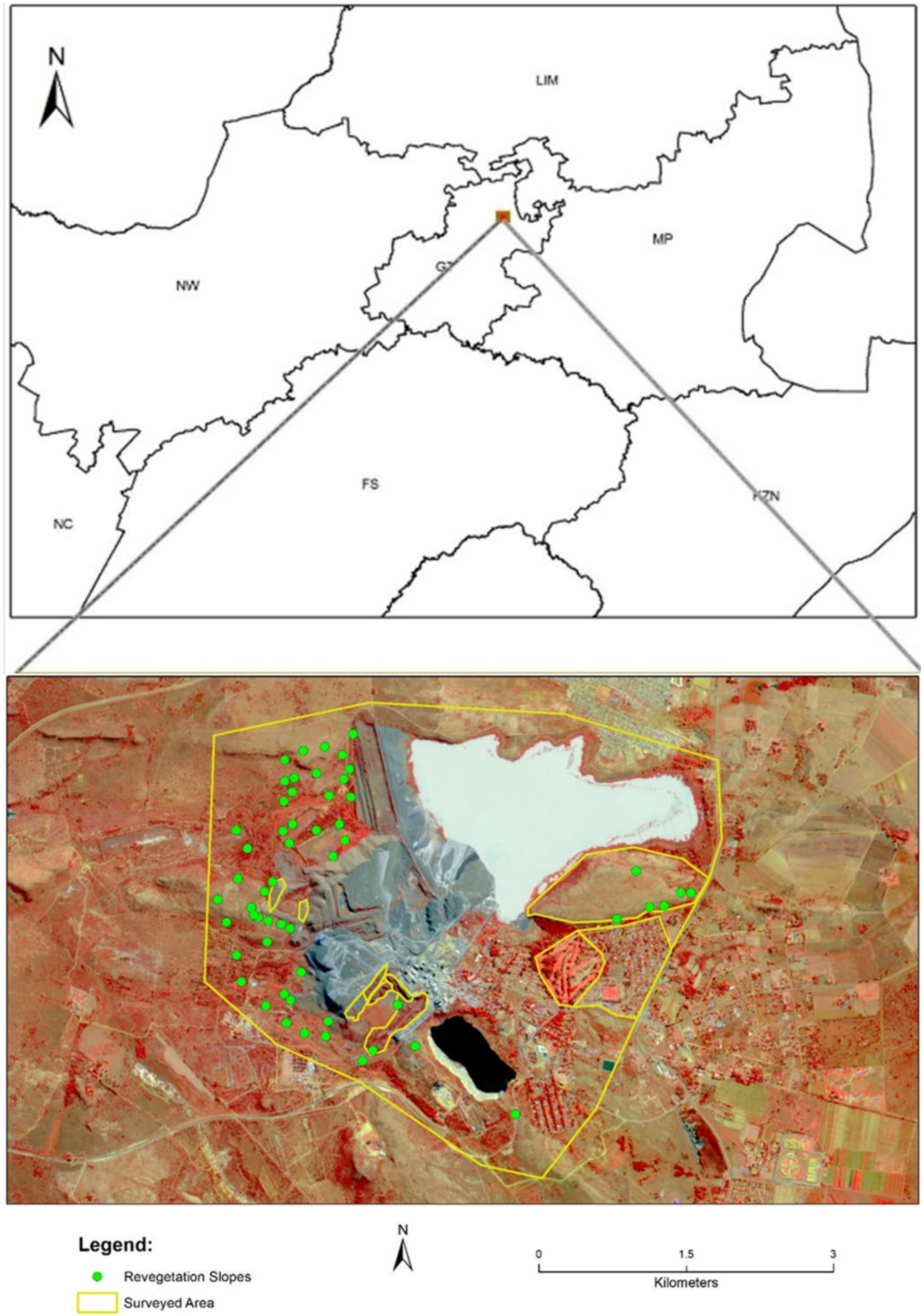

Figure 1.1 Study area showing mine tailings on SPOT-6 image (15-04-2018).

1.4.2. Climate

The average annual minimum and maximum temperature around Cullinan is 18.7^{o}c and 30^{o}c, respectively. The Cullinan area has moderate climate characterized by hot and warm summers, between September and April, and cooler winters, between May and August. The lowest recorded temperature is -6^{o}c in June and temperatures can rise up to 36^{o}c, in the warmest months (Dyson, 2009). The average rainfall received annually is 710.7 mm, mostly between October to March (South African Weather Services). The area is approximately 1350 m above sea levels, with a naturally gentle topography. However, given the type of land use, the area can be characterised as an anthropogenic topographic landscape with distinctly high-rise mine tailings.

1.4.3. Geology and hydrology

The geology of the study area is mainly dominated by underlain a diamond bearing Kimberlite. Kimberlite is named after the town of Kimberley and it denotes to potassic volcanic forms of rocks which comprise of diamonds. Kimberlite is vertical structures in the Earth's crust, namely kimberlite pipes. The geology of the area visibly manifestation to the topography which is dominated by granite and dome rock formation. The area lies in a divergence of watersheds including the Apies rives which begins south of the quartzite ranges, South of Pretoria, and drifts north. Apies connects to Pienaars River in a plain and lowland and, both rivers are tributaries of the Crocodile River (River Health Programme, 2005).

1.4.4. Vegetation

The Cullinan mine area lies in-between the plateau of the Highveld and the lower-lying Bushveld. The area is characterised by the veld type called Bankenveld, as defined by (Accocks, 1988). By Accocks' description, the Bankenveld is located between 26º E and 30º E longitudes, along with the line of latitude 26º S, and covers an estimated area of 23 568 km². Moreover, the Bankenveld veld type lies in a climatic transitional zone between sub-tropical savanna and temperate grassland type vegetation (Bredenkamp & Brown, 1998). Bredenkamp and Brown subsequently subdivided Bankenveld into various vegetation types according to climatic variation as the driving force that determines the different vegetation types within the Bankenveld vegetation.

1.4.5. Mine site rehabilitation

There were several rehabilitation activities that have been conducted at the Cullinan mine site (Figure 2), including the use of vetiver system (Truong, 2002). Vetiver grass has characteristics that are resilience to adverse climatic conditions. Vetiver system was applied at the Cullinan mine, for erosion control and slope stabilization. In South Africa, a significant number of tailings slopes have been revegetated to control erosion. However, it is very challenging to maintain tailing slopes with vegetation because of the semi-arid nature of the climate combined with the inherent steepness of tailing infrastructure (Blight & Amponsah-Da Costa, 1999).

Figure 1.2 Visual representation of some eroding tailings at the Cullinan mine site.

1.5. Outline of the thesis

This research consists of seven chapters. Chapter 1 covers general introduction providing the research context, objectives and description of the study area. The literature review is presented in Chapter 2. Chapter 3 accounts for the research methods and materials used to generate both field survey and image data, as well as the approach adopted to fuse input DEMs for the study. The results are presented in Chapter 4, including the DEM fusion and generation of slope derivates, as well as results for the analysis of remote sensing and field surveyed data for above ground vegetation canopy cover estimation. Chapter 5 Consists of discussions on the results obtained, together with the conclusions and recommendations for future work. Chapter 6 contains the references cited for this study. Finally, Chapter 7 presents supplementary information in an appendix containing a table of the input datasets used for the analyses.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The extraction of underground minerals and stockpiling of the residual waste materials as tailings expose particles which are susceptible to soil erosion. The challenge is that stockpiled soil and rock particles can be transported to downstream into rivers and low-lying areas by wind or high-intensity rainfall. In South Africa, the majority of mine tailing dams have slopes exceeding 35 % and their protection against erosion is a challenge. The major challenge is that when tailings are exposed due to lack of protection and erosion progresses beyond a certain threshold, it can cause permanent damage to the infrastructure (Dacosta & Blight, 2003). Moreover, the lack of protection often leads to accelerated erosion, which ultimately results in gullying of tailings or hill slopes. Gullying of tailings is possible when erosion agents such as runoff water accumulate over time to form rills and remove particles to considerable depths (Poesen, et al., 2013). Moreover, the process of erosion on both hill slopes and tailings can take several forms, including detachment and entrainment of the tailing material (Poesen, et al., 2013).

2.1.1. Detachment

The detachment of tailing material forms the starts of the erosion process on mine tailings. Detachment can either be caused by high-intensity rainfall or runoff water on the surface. Often high-intensity raindrops hit the surface and detach particles downslope in accumulative quantities as the rate of movement intensifies. In the process of detachment, the weight transported materials are transferred to the surface. When these particles are hit by raindrops, two potential effects may ensue: i) a consolidation force which compacts the surface or ii) imparting velocity which loosens the material and displaces it downslope (Dacosta & Blight, 2003). With an increase in steepness of a slope, raindrops become highly effective in dislodging soil and mineral particles. However, the horizontal alignment of the surface area results in fewer raindrops striking a steeper slope. During a rainstorm event, the water holding capacity or infiltration of tailing material can be exceeded and therefore, particles are detached by the force of runoff water.

2.1.2. Entrainment

The occurrence of entrainment occurs when particles are lifted because the threshold of movement is reached. Entrainment process is, therefore, the stage where the critical value of boundary shear stress is reached, depending on the type of materials making up the sediment. The sediments which constitute loosed fines and coarse grains of tailing materials are not bound together (Handley, 2018). The grain properties such as size distribution, orientation, arrangement, porosity and the degree of cohesion affect entrainment process. When sediments are transported, the materials are arranged by the size, shape and density of the particles (Handley, 2018).

The erosion rate can be influenced particle size and this is a function of velocity and the diameter of particles in the sediment load (Zhang, et al., 2011). The critical erosion velocity has been found to be less for sandy materials because such materials lack cohesion compare to other material such as clay particles. Materials with finer particles, such as silt and clay, stick together and therefore require a greater critical velocity to force the particles in motion because of their relatively stronger cohesive property. On the other hand, coarser materials such as gravel have comparatively higher velocity and this is the function of particle density greater weight (Myers, 2019). The principle of Hjulström (Figure 2.1) fundamentally affirms that the size of sediment grains is the inverse function of the flow velocity. The critical entrainment velocity for different particle sizes in relation to the propensity to be eroded.

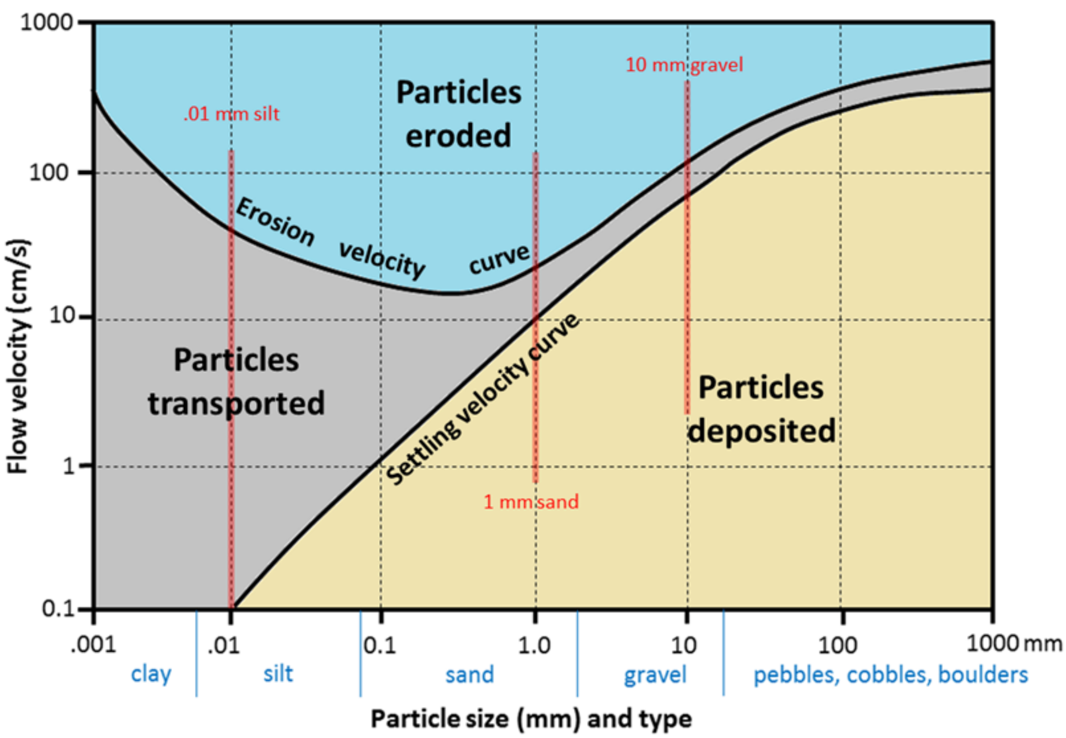

Figure 2.1 The relationships between particle size and erosion potential, transportation or deposited of particles at different current velocities (Source: https://opentextbc.ca/geology/chapter/13-3-stream-erosion-and-deposition/).

2.1.3. Erosion processes

The entrainment of unconsolidated tailing particles can be by air and rainfall water. The particles can be transported by the process of traction whereby particles roll, slide, or are shuffle along the eroding surface. Shuffling is the process whereby the particles are dragged along the tailing slope. The eroded particles can be transported whereby dissolved materials are carried along in water as individual elements, namely as stream load (AGI, 2018).

2.2. Types of erosion

2.2.1. Sheet erosion

The process of sheet erosion occurs when splashing raindrops result in runoff and removal of a thin layer of surface topsoil. Splashing raindrops on bare soil can disaggregate and dislodge the particles (AGI, 2018). The process of sheet erosion usually happens progressively to cause instability along the flow projection. However, sheet erosion is detected by the presence of soil deposition at the foot slope. The process of sheet erosion if not mitigated can quickly erode mine tailings material downslope (Swart, 2004).

2.2.2. Rill erosion

Rill erosion occurs when small distinct channels develop as a result of the concentration of surface runoff (Swart, 2004). Therefore, rill erosion can be triggered after sheet erosion, under a high-intensity rainfall. Rill erosion can be identified as a series of small channels of about 300 mm incision on the surface (Richter, 2011). Under conditions of repeated or increasing rainfall, the surface water exceeds critical infiltration level, and the small well-defined channels commence to deepened and develop into bigger channels. Subsequently, the sheer power of the water in the bigger channels separates entrained particles and transport them along the defined trajectory of the channels. Rill is the transition stage between the sheet and gully erosion (Swart, 2004).

2.2.3. Gully erosion

Gullies erosion initiate after rill erosion, as open erosion channels of at least 30 cm deep incision on the surface (Swart, 2004). Gullies are a result of erosion of head-cuts in the direction of a drainage-way. For a land surface with the influence of mine tailing dams, gully erosion can be initiated from the rill features on tailing slopes. Gullies expansion by the process of sidewalls sloughing off and movement of debris in the channel. Figure 2.2 shows an example of mine tailings and nearby gullies erosion.

Gullies can be classified according to their position in the landscape, shape and form of the cross-section, the type of soil and the temporary or permanent state of a gully. There are six characteristic gully forms including compound, bulbous, linear, dendritic, parallel, and trellis gullies (Poesen, et al., 2013). With regard to gully position in the landscape, there are valley-floor, valley-side and valley-head classes of discontinuous or continuous gullies.

Figure 2.2 Examples of erosion on diamond mine tailings with Kimberlite material and land surface erosion (Photos: Copyright of Diamcor Mining Inc., http://www.diamcormining.com).

2.2.4. Channel erosion

Channels are formed as the final stage of erosion as the concentrated pathway for running water leaving. Channelling can be mitigated by decreasing the volume and rate of runoff (Blight & Amponsah-Da Costa, 1999). Downward scouring due to the sheer stress of the repeated flow of water causes channels expansion. The erosion potential intensifies depending on the volume of flow, the velocity of runoff and depth of the channel, as well as sidewall sloughing due to large flows (Swart, 2004). For the case of tailings, the cumulative erosion on the slopes can result in gullies and can cause a shear failure of the tailings dam wall (Castillo & Pintor, 2010).

2.3. Factors affecting erosion

The factors affecting erosion can be identified as four principal factors including the climate, soil characteristics, topography and ground cover. The following subsections discuss the various factors influencing evolution and dynamics of surface erosion.

2.3.1. Climate

Climate is a significant physical factor which directly or indirectly affects the evolution and development of erosion. Climatic variables such as rainfall is an agent of erosion and a driving force for dislodging materials and transporting them along with the runoff water. Climate and associated prevailing weather determine the intensity, duration and the size of runoffs. Moreover, the erosive power of rainfall is depended on the duration and intensity (Sheoran, et al., 2010).

2.3.2. Types of materials and their characteristics

Erodability of a surface is a function of, but not limited to the texture, structure and permeability of the materials constituting the surface (Sheoran, et al., 2010). In general, surface materials with higher infiltration rates and good structure have a greater resistance to erosion. The texture of surface material is considered as its size and weight proportion of the particles making up the type of material (i.e. mixtures of soil, stone and rock). Coarse-textured material aggregates allow water to infiltrate easily to reduce the potential for runoff compare to surface with fine-textured material such as milled slime-dam stockpile.

2.3.3. Topography

Topography factors such as slope length and slope steepness influence runoff velocity. The shape of the slope also affects the erosion potential. It has been found that the apex of a slope is more prone to erosion compared to the foot slope which receives the transported material (Dacosta & Blight, 2003). Steeper slopes have greater potential to effect movement of material along the slope. Dacosta and Blight (2003) found that the highest erosion occurs between 25^0 and 35^0 slopes, which is typical specifications for most mine tailings.

2.3.4. Ground cover

Ground cover is when the natural landscape or anthropogenic surface is protected from the adverse effect of erosion agents. Constructing ground cover often consists of the use of materials such as vegetation residues, sawdust, jute netting and chipped rocks. Moreover, planting green vegetation as the ground cover is considered the most effective way of protecting a surface against erosion (Paredes, et al., 2015). Vegetation as a ground cover helps to shield surfaces from the impact of rainfall, slowing down runoff, binding of soil particles or surface material. The usefulness of vegetation cover for erosion control depends on type material (i.e., physiological traits), the extent of coverage and the density of the plant species (Sheoran, et al., 2010).

2.4. Erosion models

Erosion on slopes of manmade surfaces has been a concern to environmental professionals working on landscape restoration projects. In this context, it is important to understand the factors affecting erosion rates. There are two fundamental types of erosion models namely, the process-based models and empirically based models. Process-based models depend on physical-mathematical principles to describe the erosion phenomena of detachment, transport, and deposition of loss soil and other materials on the land surface areas. Notably, there are no completely process-based models which do not integrate aspects of empirical data (Gray & Sotir, 1996). Hence, for centuries, researchers have study erosion on different surfaces using experimental plots under field conditions or rainfall simulator experiments to calibrate a number of empirical erosion equations. The primary erosion equation is the Universal Soil Loss Equation (USLE). Smith et al. modelled the long-term average annual soil loss: (A) = RKLSCP, whereby R and K are respectively the rainfall erosive and soil erodability factors, L and S are topographic factors, and C and P and management factors (Smith, et al., 2001). The USLE equation does not estimate gully erosion and sediment delivery (Gray & Sotir, 1996).

2.5. Erosion of tailing slopes

2.5.1. Soil erosion and erosion prevention

Tailings and associated unconsolidated rock piles of waste materials are common sources of erosion within the mining industry. Slopes of tailings dams are usually steep and therefore, susceptible to erosion. Methods for erosion protection on tailings can include the use of cement and covering surfaces with stones. Other methods involve covering a surface with vegetation, gravel and boulders to reduce erosion. However, tailings slopes in South Africa are difficult to maintain partly due to the challenge of establishing vegetation on most tailing dams (Truong & Hart, 2001). Therefore, research is focused on investigating the efficacy of vegetation species that have traits to enable their establishment on mine tailings.

2.5.2. Gullies on slopes of tailings dams

Gully development on tailings slopes can be influenced by various factors such as the kind of mineral composition of the disposed of material and the timeframe of tailings exposure to erosion agents (Balice, et al., 2000). Whilst soil erosion in the early stages can be prevented, once the problem advances to gullies, it can be more difficult to solve. Mining companies often construct crest walls to stop water accumulation and downslopes flow. Crest walls are also used to retain already eroded tailings. Another method is the introduction of berms along the slopes of tailings to combat erosion (Dacosta & Blight, 2003).

2.5.3. Rehabilitation of tailings dams

Rehabilitation of tailings dams is a long-term process of maintenance and environmental monitoring. Erosion on tailings can be controlled using several approaches including compacting tailing materials inside eroding surfaces, levelling the gully sidewalls, or revegetating tailing slopes. The use of vegetation has proof affordable and efficient in restoring land affected by mining operations and has been at the top of the recommended techniques for rehabilitation of landscapes (Truong, 1999). It has been commonly used in the past as the most common effective technique for preventing erosion (Truong, 2000).

2.6. The Vetiver System

2.6.1. Introduction

Known to be highly tolerant to heavy metals in soils and resilient to extreme weather conditions, the Vetiver grass (*Vetiveria zizanioides*), technically referred to as the Vetiver System has been successfully implemented for soil and water conservation in several agro-ecological applications. Moreover, the use of the Vetiver System as a bioengineering solution for erosion control and slope stabilization is a traditional technique that has gain increased popularity in recent decades.

The Vetiver grass has exceptional characteristics which make it suitable for rehabilitation of erosion and slope stabilization. The unique characteristics of Vetiver grass include its giant, tufted, perennial, fragrant grass, normally with a straight stalk. It has extensive slender leaves and deep rooting system that is profuse, multilayered, and widespread (Chomchalow, 2001). The grass is normally cheaper but effective and environmentally friendly to control soil erosion and for restoration purposes. The roots of the vetiver have been used for many years especially in Asian countries. It is used for producing perfume and for making scented floor-covering as well as shelters. The vetiver grass also comprises of vigorous ingredients used for medicinal purposes and as a botanical insect killer (Chomchalow, 2001).

There has been growing concerned globally on the pollution on the environment due to the discarding of byproducts agricultural, manufactural and mining industries. Most of these byproducts are polluted with heavy metals which have an impact on both fauna and flora ecosystem. The growing concerns about pollution from disused mines and lands have led to regulated guidelines formulated. These guidelines protect and prevent effluence of heavy metals from disused mines. In most instances, industries follow applicable techniques of rehabilitation or stabilization is implemented. The techniques used to control soil erosion and slope stabilization of polluting chemicals from industries include removing the effluence from the affected land or burying them. These methods are very costly and difficult to enhance because of large volumes of the discharged waste of chemicals. For example, Gold and coal tailings often have large affluence and it cannot be treated or detached (Truong, 1999). Then it must be prohibited from polluting the surrounding areas.

The vetiver system is used in disused mines, cultivated areas and roadsides. The other uses of vetiver include thatching, rope making, and weaving baskets (Chomchalow, 2001). Vetiver has unique morphological and physiological features that are tolerated to polluted water wastes from disused mines. Vetiver grass has a deep rooting system that is tolerant to harsh climatic conditions which include floods, drought, wildfire, submerge, Heat and cold. The vetiver is also tolerant to extreme acidity soil with heavy metals like salinity, alkalinity, Zinc, lead, Mercury, Manganese and copper. These heavy metals are usually found in disused mine tailing and with a lower Ph, there are easy dissolved (UNEP, 2013). There have been successful research that shows how vetiver is proving to be the best system to rehabilitate disused mine tailings and landfills different countries globally. Land that is polluted from discharged chemicals of industries and mining when vetiver is used it possesses an exceptional characteristic.

Although vetiver system has proved to be the most preferred vegetation technique in various countries, however, it is usually a challenge because it’s slow to grow. The harsh climatic conditions and the presence of chemicals in the soil often make the vetiver system to take longer to grow. In the past years, vetiver has been used successfully in countries like China, India, Brazil, Australia, and Nigeria. These countries have different climatic conditions. For example, in China vetiver is used for slope protection of tea and citrus fruits while in Trinidad it is used to stabilize the sides of the roads (Greenfield, 1989).

The vetiver system was established depending on the application of vetiver grass. In recent years, the vetiver has been used for agricultural areas and for scientific research. The scientific researches that have been conducted indicated the vetiver is effective, modest and a cheaper system for slope stabilization and protect the environment from soil erosion. For this reason, vetiver is progressively been used globally (Truong, 2000). The major reason that has contributed to the international acceptance of the vetiver system is the accessibility of information, data and various field observations that have been carried out. This provides the necessary information about the incredibility and exceptional physiognomies of the vetiver system. There is online information that is readily available through The Vetiver Network (Truong, 2000).

2.6.2. Morphological characteristics of Vetiver grass

The vetiver grass is known for a wide range of application because of its distinctive morphological and physiological characteristics which are adaptive to varieties of ecological conductions. Vetiver system is presently used in 120 countries globally for slope stabilization, soil erosion, agricultural activities, pollutant soils and rehabilitation of disused mines (Truong, 2002). The vetiver roots are used for the production of perfume and oil. However, there is a debate on the roots of vetiver that when harvested for the production of aromatic fragrance it intensifies erodability by the loss of soil. The rooting system of the vetiver comprises of fibrous roots which attribute to a distinctive morphology. The root grows up to 3 metres deep and provides the grip needed to prevent soil erosion during storm, drought and floods. It can also withstand a variety of temperatures as below as -14°C to 55°C. It has stiff leaves which prevent soil debris in instances of a heavy storm. Vetiver has hedges which make the runoff to be sluggish and as a result preclude rills and gullies. Vetiver is a low cost and environmentally friendly method of controlling soil erosion and slope stabilization in disused mines and agricultural lands (Mickovski, et al., 2005).

Globally approximately 2,500 industrialized mines are functioning, but only a few of these mines dispose mine tailings on sites. In most cases, these mines use rivers, lakes, oceans or dams. There are few countries with mining activities that are permitted to dispose of their mine tailings into rivers and marine waters. Since vetiver is cheaper for slope stabilization, soil erosion, mine tailing and conservation, the World Bank and The Vetiver Network have been creating awareness of its uses. The promotion of the vetiver system has information available on websites for both the World Bank and The Vetiver Network (Truong, 2002). This is to encourage people to learn about the vetiver system as well as utilize the information provided on the website for sustainable and ecological conservation.

2.6.3. Physiological characteristics of vetiver grass

The Physiological features of vetiver grass include been tolerant to a wide range of heavy metals. These heavy metals are Manganese, Zinc, Mercury, Cadmium, Nickel, Arsenic, Selenium, Aluminum, and Chromium (Lavania, 2008). The main reason why vetiver is suitable for rehabilitation of abandoned mines tailings is that of being tolerant to heavy metals (Pang, et al., 2003). It is tolerant of harsh climatic conditions like drought, submergence, high temperatures, and floods. The other physiological characteristic of vetiver it can survive in extreme temperature ranging from - 14ºC to 55ºC. Vetiver is known for blooming under heavy rainfall ranging from as much as 300 mm to 6000 mm annually (Pang et al., 2003). It has the capacity to regrow promptly when affected by natural disasters such as floods, drought, wildfires, snow, salt water and other hostile circumstance. According to Truong (1998), Vetiver grass can survive soils with pH 3.0 to pH 10.5.

2.6.4. History of Vetiver grass

Vetiver is a native Indian grass which can grow up to 3 meters in height and have a deep rooting system. The roots of vetiver grass can grow 3 to 4 meters deep making it extreme drought and cold condition tolerate. The vetiver grasses are used for safeguarding contours for the past years. The National Botanical Gardens in 1956 came up with an initiative to rehabilitate disused mines and to prevent soil erosion. This is by slope stabilization and soil modification in disused areas (Lavania, 2008).

Although vetiver grass has played a significant impact on the protection of land worldwide for the past 50 years, its actual effect became enlightened in 1980. The vetiver system was developed by the World Bank for soil and water preservation purpose. Numerous researches that have been conducted in various countries globally show positive results. This led to the establishment of The Vetiver Network International (TVNI) by (Grimshaw, 2003). The main aim of the network is to provide information on the use of the Vetiver System (VS). It also promotes the global use of the Vetiver System for a justifiable environment predominantly in relation to soil erosion control and water conservation (Truong et al., 2002).

The application of the VS for soil erosion and slope stabilization in disused land still plays an important role. In agricultural areas, the VS has proofed to tolerance to exceedingly soil conditions plays a significant role in the protection of the environment in a sustainable way. The vetiver grass has unique physical and morphological attributes that provide opportunities for engineering applications for conservation (Truong, 2000).

2.6.5. Vegetation and biotechnical erosion prevention

Erosion of surfaces can be done using defined biotechnical or bioengineering techniques. Biotechnical control involves the use of plants materials to protect slopes from erosion (Gray and Sotir, 1996). Revegetation of slope for controlling erosion is called soil bioengineering. Moreover, the use of soil bioengineering is considered as a subset of biotechnical stabilization. With this process, plant roots and stems are the main structural components for the protection of slopes (Gray and Sotir, 1996).

The sowing of seeds to revegetate a land surface is a practical rehabilitation approach for long-term and sustainable erosion control method (Pennock & De Jong, 1987). The role of different vegetation types for controlling erosion by stormy winds or rainfall. For example, maintaining a dense cover of grasses, or vegetation can decrease soil losses.

2.7. Relevant case studies

2.7.1. Australia

There are numerous case studies that have been conducted in various countries globally to show the effect of the Vetiver system on erosion and slope rehabilitation in disused mines. An experiment was conducted to choose the most appropriate vegetation type for the rehabilitation of coal tailing which had 23 hectares. This experiment was done in Queensland Australia. The substances used were saline, extremely sodic and very low in nitrogen and phosphorus (Truong, 2002). These substances had delimited intensities of solvable sulfur, magnesium as well as calcium.

The vegetation type had high levels of copper, zinc, magnesium, and iron which were high present. However, there were five salt vegetation type of vetiver grass used which is tolerant to salt. These vetiver types include saltwater couch (*Sporobolus virginicus*), reed grass (*Phragmites australis*), cattail (*Typha domingensis*), vetiver grass (*Vetiveria zizanioides*) and saltworts (*Sarcocornia*). These vegetation types were kept for 210 days for comprehensive mortality excluding vetiver and saltwater couch (Truong, 2002). There was mulching which was taking place at a considerable rate in vetiver. After the application of fertilizer on the vetiver, there was no consequence.

2.7.1. South Africa

In South Africa, there are different rehabilitation experiments that were conducted by De Beers. These were conducted on tailings dumps and slimes dams at various sites, the out coming from these experiments discovered that vetiver retains all the essential characteristics which are ecologically sustainable in terms of growth on kimberlite plunders (Truong, 1999). It was also discovered that vetiver developed strongly on alkaline kimberlite which comprises of runoff, stunning loss of soil while producing an ultimate micro-habitat for the formation of native grass types.

The use of vetiver grass for rehabilitation was predominantly effective on kimberlite in South Africa at Cullinan mine. The mine has a gradient which is sloppy and can sustain hot of approximately 35^{o}c to 40^{o}c (Truong 1999). Therefore, vetiver grass has been effective on the rehabilitation of soil erosion, slope destabilization of disused mines, agricultural land, highways and polluted areas. VS has been successful in rehabilitation and stabilization of mining tailings. Hence there are vetiver nurseries that have been established at various mining areas as a result.

Other mines using vetiver grass include Anglo American Platinum in Rustenburg as well as the President Brand gold mine in Free State for the rehabilitation of disused mines (Truong 1999). The different researches conducted on vetiver grass in Australia and South Africa the results show that the application of the Vetiver System is extremely appropriate for rehabilitating contaminated disused mine wastes as well as tailings. For vetiver to be effective the application of this technology, it is important to fully have the knowledge of understanding of the biochemical properties and the resources necessary rehabilitation processes.

2.8. Remote methods and topographic measurements

With the advent of advanced remote sensing approaches for generating high-resolution digital elevation model (DEM) data, it is increasingly effective to characterised geomorphic features using DEM-derived topographic variables (Hawker, et al., 2018; Betts & DeRose, 1999). In particular, remotely sensed DEM data combined with ground observations have been directly used to measure changes in hillslopes due to surface erosion (Hsieh, et al., 2016). Moreover, topography affects the landscape morphology and evolution of vegetation species. The calculation of topographic variables is therefore important in the study of the topographic influence on vegetation establishment and sediment transportation.

The methods for deriving DEM data can include various techniques of processing remotely sensed optical images, stereoscopic measurement of Synthetic Aperture Radar (SAR), laser point cloud scanning, and photogrammetry (Lillesand, et al., 2015). With advancements in the development of these technologies, access to DEM data has improved and therefore, have been extensively applied in topographic research (Hawker, et al., 2018). High spatial resolution DEMs with high-height accuracy can effetely characterize the topography in terms of slope steepness, length and orientation. Moreover, collecting sufficient field point data is important in updating remotely derived DEMs for the successful characterisation of hill slopes or measuring changes in anthropogenic topographic terrain. For example, Kakembo et al (2009) used DEM to extract topographic slope features for the estimation of the gully erosion, and they found a linear relationship between the terrain slope and the vegetation cover which is associated to different land uses.

Using this relationship, the distribution of gully within the communal areas of the Eastern Cape Province in South Africa was inferred by a DEM slope map. This shows that derivatives of DEM can depict the distribution of gully erosion and the erosion pattern in relation to topographic slope steepness, phase or orientation and can also be used periodically to observe topographic changes in the landscape (Kakembo, et al., 2009). Studies such as this demonstrated that DEM analysis techniques can provide a good estimate for direct observation of changes terrain associated with gully erosion.

2.8.1. Fusion techniques and digital elevation models

Digital Elevation Models (DEMs) provide topographic information including terrain slope, orientation, and height. Traditionally DEMs were derived at the local or national level through field-based surveying of terrain points or stereoscopic measurement of contour lines (Hawker, et al., 2018). The advent of advanced photogrammetry and remote sensing has made it possible to effectively acquire terrain data over large areas to generate both national and global datasets. Moreover, DEMs form the basis for geometric rectification of satellite imagery and orthophoto generation. DEMs are used for advanced geo-visualization, 3D-modelling and integrated into data analysis in different application fields, including but not limited to geology, applied geomorphology, hydrology, and urban planning.

DEMs are usually supplied in dimensional raster representation and available from several sources, covering almost any region of the globe (Hawker et al. 2018). Some of the commonly available global DEMs includes the 30 m grid spacing RSTM

(Shuttle Radar Topography Mission), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM, TanDEM-X and the Reference-3D which is generated by stereoscopic analysis of SPOT-5 optical satellite image data. In that regard, there is a redundant availability of multi-source DEMs with varied spatial and height resolutions. The interesting question is how to leverage by fusing two or more DEMs and generate an output that is more accurate than any of the inputs. It is therefore important to then assess common fusion approaches for deriving point information for fusion analysis.

The common method for DEM fusion is by weighting averaging whereby the output DEM is derived by subtracting the residual values of the input DEMs (Karkee, et al., 2008; Yu, et al., 2018). DEM fusion can also be computed by generating a prior approximation of the terrain surface. With this approach, the least squares adjustment is implemented to derive the most higher surface values in the output DEM (Yu, et al., 2018). Also, fusing has been done by interpolating the frequency domain of the input DEMs to derive a more accurate one (Hosford, et al., 2003).

With existing DEMs of comparable accuracy, it is possible to possible to update an existing DEM through on the ground 3D point measurements. Such an approach incorporates recent changes in the landscape topography into an existing DEM. However, this approach has the conceptual weakness that makes it difficult to establish whether the employed fusing technique is compatible with the method used to generate the original DEM (Xu, et al., 2010). Despite such a weakness, several studies perform DEM fusion using the simple weighted averaging algorithm in combination with on the ground measurements (Karkee, et al., 2008). For example, Karkee et al. fuse ASTER and SRTM DEMs through resampling the input DEMs to the same grid and the calculated an output value for each grid with ground observation included to achieved 42% improvement in accuracy.

2.8.2. Optical remote sensing and estimation of vegetation cover

Remote sensing methods increasingly offer an effective technique of estimating vegetation cover in a consistent and timely manner over large areas. The application of remote sensing data in mining landscape and rehabilitation research is common practice. The science and art of applied remote sensing are well-established to obtain information about vegetation cover dynamics using both optical and SAR techniques (Haupt, 2018).

Remote sensing technique for mapping vegetation cover offers the advantages of large area coverage, consistent and frequent access to increasingly high-resolution data. Moreover, it has been established that monitoring the evolution of vegetation cover for erosion control is important in environmental planning and provides timely information for decision making in the area of landscape pollution. Remote sensing approaches have been effectively applied in the assessment of vegetation cover of anthropogenic mining landscapes (Haupt, 2018; Blaszczynski, 1997; Betts & DeRose, 1999). However, the mapping vegetation cover type on rehabilitated or active tailings can be challenging due to the spectral complexities of discriminating between natural vegetation cover and revegetated cover types.

Another challenge is that mining landscapes are composed of very steep tailings slopes or open pit backfills of up to 35%. Such topographic features have well-establish to cause geometric distortions which in turn impact on the recalibration of radiometric data of corrected multispectral images (Shao & Zhang, 2016).

Multispectral vegetation indices have been widely used to estimate vegetation cover classifications. Commonly used multispectral vegetation indices are the dimensionless ratio of the combination of spectral bands. The main advantages of vegetation indices are to reduce noise the spectral feature space and optimise band-sensitivity to the target parameter of interest (Huete, et al., 2002). The Normalized Difference Vegetation Index (NDVI) formulated by Tucker and Sellers is the commonly known and widely used indicator of vegetation condition (Tucker & Sellers, 1986). Several studies have used the NDVI to monitor and evaluate vegetation cover of rehabilitated mine sites (Limpitlaw, 2006; Haupt, 2018).

Despite its wide applications in monitoring vegetation dynamics, the use of the NDVI is well documented to be susceptible to saturate under high vegetation biomass (Mutanga & Skidmore, 2004). However, vegetation density of arid and semi-arid tailings environments is often low, and there does not constrain using NDVI. For example, Karan et al compare NDVI and the Enhanced Vegetation Index (EVI) to assess rehabilitee of coal mine areas and found that NDVI and EVI achieved comparable results (Karan, et al., 2016). The EVI was developed to be more sensitive to changes high biomass, minimise the attenuation of spectral due to atmospheric conditions and account for the background signals scattering of vegetation canopy (Huete, et al., 2002). In this regard, Huete et al (2002) found that even though NDVI is sensitive to canopy chlorophyll content, EVI is more sensitive to the canopy structural differences, which relate to the leaf area index (LAI) of specific canopy type.

CHAPTER 3: RESEARCH METHODS AND MATERIALS

The current research is set put to explore DEM fusion and optical remote sensing feature extraction to characterize topography and estimate vegetation cover. Multi-source DEMs and high-resolution remote sensing image data were obtained for preprocessing and further analysis. The methods followed two separate workflows: i) perform DEM-based data fusion analysis for generation of a more accurate one and, ii) explore image feature extraction and simple linear regression for vegetation canopy cover estimation. The output map was then used to evaluate the success of revegetation strategies on some mine tailings slopes at the Cullinan study area. The following Section 3.1 and Section 3.2 describe the processing steps respectively, for the fusion of input DEMs and calculation of topographic variables of interest. Section 3.3 describes the combination of field survey and optical remote sensing data for vegetation cover estimation. Finally, Section 3.4 discusses the accuracy assessment approach followed to validate the methods.

3.1. DEMs and fusion analysis

3.1.1. DEM data preparation

The remotely sensed data acquired for this research was a 30m spatial resolution SRTM Version-3 DEM (Figure 3.1A). The SRTM DEM was derived using Interferometric Synthetic Aperture Radar, namely, InSAR technology. A void-filled SRTM DEM data covering the study area was freely downloaded from the NASA Land Processes Distributed Active Archive Center (LP DAAC) (https://gdex.cr.usgs.gov/gdex/). The data is delivered with the WGS84 coordinate system and voids in the data were filled with ASTER Global Digital Elevation Model (GDEM) Version 2.0. The original global SRTM data was collected on 02/11/2000 covering 60° north to 56° south of the equatorial line. The Kinematic Global Positioning System Geodetic field surveying method was used to validate SRTM DEM data (Rodriguez, et al., 2006). The actual vertical height error (RMSE) has a root mean square error less than 16m, and a relative vertical height error of RMSE less than 10m (Farr, et al., 2007).

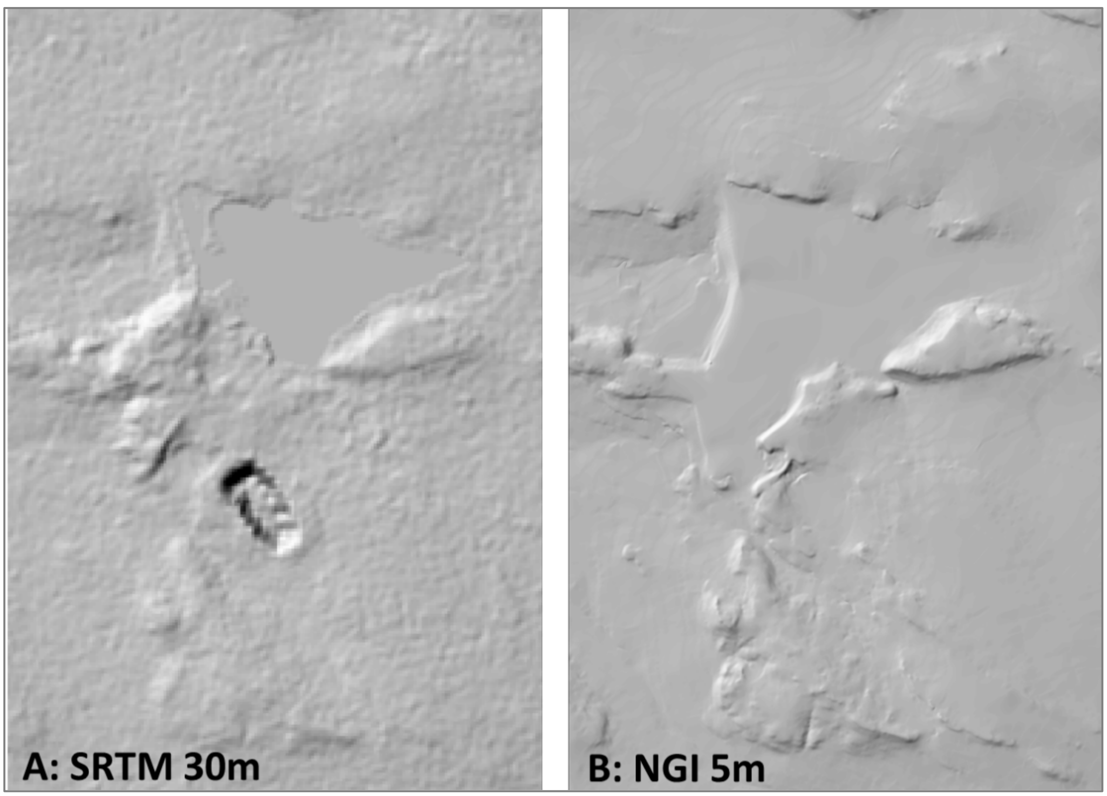

Figure 3.1 Shaded relief (Hillshade raster) of the SRTM DEM (panel A) and cdDEM-5m (panel B), respectively.

The second DEM (Figure 3.1B), namely, cdDEM-5m data based on 5m grid cells were acquired from the Chief Directorate (CD): National Geospatial Information (NGI), only at the cost of shipping. This package also contained the publicly available 1:10000 scale, vector datasets of the 5m contour line and spot heights. In addition, elevation measurements were collected using a GPS instrument and combined the contours and spot height dataset for use as reference data.

As a principle of geospatial analysis, preprocessing of data must precede analysis, particularly, when dealing with multi-source DEMs of inconsistent datum and data formats. The preprocessing approaches primarily followed three steps: i) co-registration to transform the horizontal and vertical datums of all DEMs into common horizontal and vertical axis based on the WGS84 projection with local longitude set lo27 transformation, ii) resampling of the DEM with coarser resolution to that of higher-grid resolution, and iii) applied low-pass and high-pass filters to remove inaccurate terrain components from both input DEMs for further analysis (i.e. combining into a single, more accurate output DEM).

3.1.2. Fusion of DEMs

A workflow was experimentally developed and applied to implement a fusion of the already pre-processed SRTM 30m and cdDEM-5m 5m DEMs. The initial step followed in performing the fusion technique was to co-register the input datasets to a common projection, and then resampling the 30m SRTM DEM to 5m higher resolution grid sing the RESAMPLE function of spatial analyst extension. Next, co-registration of the inputs was performed and the outputs converted to a common data type using the Bilinear Technique. The MOSAIC function is then used to fuse together the resampled the two DEMs. For the process of mosaicking, the following equation was applied: output1 = mosaic (SRTM30m, cdDEM5m). The MOSAIC function adopted uses Weighting Averaging algorithm to output the resultant fused DEM. The MOSAIC function with Weighting Averaging was selected based reasons discussed in Section 2.11. The output single band 5m DEM was subjected to accuracy assessment by comparison with values from the reference elevation data. Figure 3.2 shows the approach followed to calculate the single layer fusion algorithm.

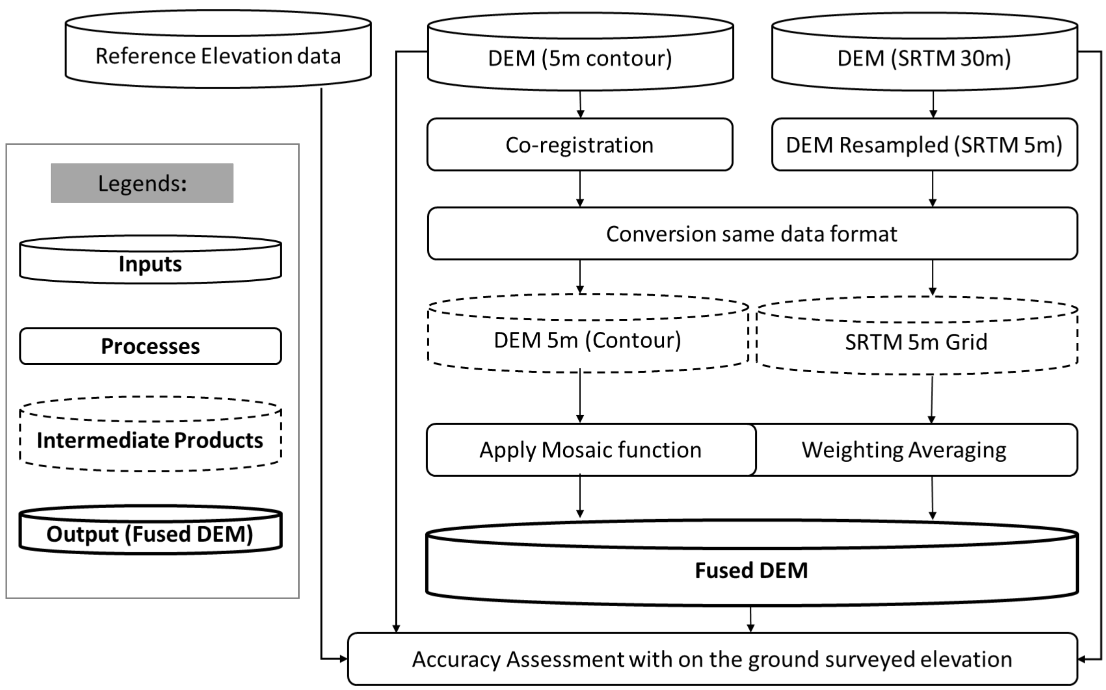

Figure 3.2 Workflow of the DEMs fusion algorithm: algorithm adapted after Karkee et al (2008).

3.2. Derivation of topographic Variables

3.2.1. Elevation, slope and aspect transformation

Topographic elevation, slope gradient and aspect influence landscapes geomorphology. These variables partly explain the spatial dynamics in aboveground cover, structure and patterns of vegetation response to environmental change. The elevation data, stored as the z-values in the output DEM generated in Section 3.3 was extracted using the Zone Statistics as Table Function in Spatial Analyst for further analysis. Slope gradient or the rate of maximum change in elevation from each raster grid of the DEM was calculated using the Slope Function in Spatial Analyst. The output slope is expressed as percentage (%) rise, whereby a flat surface is 0% increasing percentage rise as the surface becomes more vertical. The Slope Function fits a 3x3 raster grid in a neighbourhood and assigns the output rate of maximum change to the centre grid. The output slope was further processed by using the Resample Function to classify the layer into intervals of 5% slope rise up to 35% and above 35%. The reclassification of the slope layers was done to ease interpretation of the slope in relation to the revegetation effort in the study area. Moreover, the Spatial Analyst tool was used to calculate the orientation of the slope as the aspect for each grid cell. The Aspect Function calculates the orientation of the slope clockwise from the north and expressed the output in positive degrees from 0 to 360, with zero or flat slopes assigned an aspect value of -1.

3.2.2. Site exposure index

Topographic site exposure index, namely SEI is a quantitative approach for the calculation of heights and distances of a horizon relative to its surrounding area. It can be calculated by rescaling aspect of DEM grid cells to a north/south axis and weight them by the steepness of their slope value (Balice, et al., 2000). SEI value ranges from -100 to 100, representing the coolest to warmest locations respectively. SEI is an important variable which represents the degree of surface exposure to factors such as wind, which is a significant agent of erosion. DEMs provide the fastest and efficient method for calculation SEI and therefore limit the amount of fieldwork needed to collect site exposure information.

3.2.3. Surface curvatures

Different kinds of surface curvatures of topography represent the accentuation of different aspects of a slope. Therefore, surface curvatures are used as a good indicator for soil erosion patterns as well as for describing the movement and distribution of water on a slope (Di Stefano, et al., 2000). Curvature values provide useful information for understanding erosion and runoff processes. For this research, potential movements of material along the slope, from high elevation to the bottom of the slope is assessed by modelling the shape (i.e. convex, concave or uniform) of the flow path. The Curvature algorithm was implemented using ArcGIS/ArcInfo 3-D analyst. The algorithm calculates second derivatives of slope surface and outputs three layers, namely:

i) **Profile curvature** – affects acceleration and deceleration of material movement across the surface and, consequently influences erosion and deposition. Profile curvature runs parallel to the direction of maximum slope. Negative Profile values indicate upwardly convex-shaped surface which affects deceleration of flow. Conversely, positive profile values indicate an upwardly concave surface with accelerated effect on flow. A zero-value specifies a surface linear profile.

ii) **Planform curvature** – influences convergence and divergence of movement on the surface. Commonly referred to as the Plan-curvature, the Planform curvature runs perpendicular to the direction of the maximum slope. As such, positive plan values indicate laterally convex surface, whilst, negative plan values indicate laterally concave surface. Similarly to the Profile curvature, a zero value of pan indicates linear a surface.

iii) **Standard curvature** – this curvature model combines the profile and planform curvatures, therefore, considers the influences of both plan and profile curvature to allow a more accurate representation of the material movement across a slope.

3.3. Remotely sensed data analysis

3.3.1. SPOT-6 data acquisition and pre-processing

The *Satellite Pour l'Observation de la Terre* (SPOT), namely SPOT- 6 satellite carries an optical imaging payload capable of imaging, respectively, a 1.5 m panchromatic and 6 m multispectral (blue, green, red, near-IR) resolutions.

Launched September 9, 2012, the main mission objective was to provide remote sensing imaging products useful in several application areas including defence, agriculture and forestry, monitoring and surveillance in environmental and mining sectors. SPOT-6 have been in operation since 2014. This satellite is equipped with reactivity capacity for tasking images, product delivery and collection.

Together with its twin satellite, SPOT-7 which was later launched on June 30, 2014, the constellation of the two satellites is providing a near-daily global revisit with total coverage of 6 million km^2 per day. The satellites nominal mission life is 10 years. The SPOT-6 scene data for this research was acquired from the South African National Space Agency (SANSA).

The SPOT-6 image data of 15th April 2018 corresponds with to the field survey campaign which carried out February and April 2018. The SPOT-6 data was acquired already pre-processed to the bottom of the atmosphere using the ATCOR atmospheric correction algorithm (Richter, 2011) in PCI Geomatica Software (PCI Geomatica, 2017). According to the metadata of that accompanied the imagery, PCI Geomatica 2017 software release was used to convert the SPOT-6 DN number to surface reflectance measurements. Figure 3.3 is a representation of the wavelength locations of SPOT-6 bands and in relation to some vegetation spectral profiles.

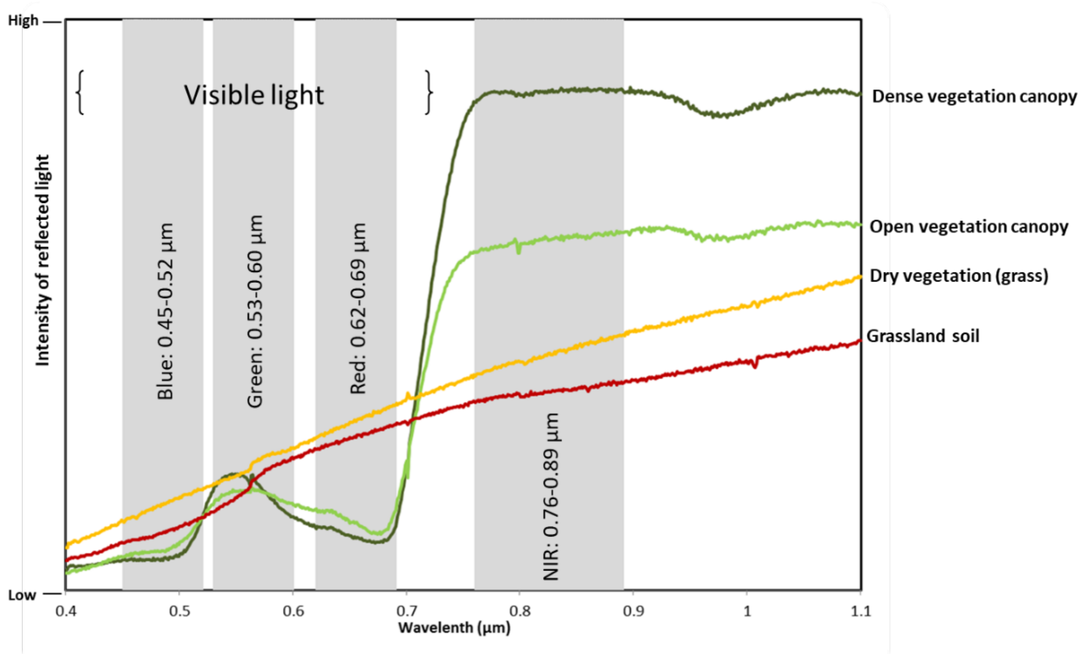

Figure 3.3 Showing the SPOT-6 spectral bands (grey-colour bars) against the spectral profile of different vegetation canopy types.

3.3.2. Field materials and preparation of SPOT-6 imagery

SPOT-6 image processing was conducted using the ArcGIS/ ArcMap10.4 software version. Some image analyses were carried out using the ENVI 5.3 software version. Field data on vegetation canopy survey was conduct by both visual assessment and canopy gap estimation using a measuring tape, in a 10m X 10m sample plots. As recommended by (McCoy, 2006), the set plot size is considered sufficient for use in calibrating both the 5m DEM grid cells and 6m spatial resolution SPOT-6 derived NDVI image. The centre coordinates of plots located on selected old tailings and hillslopes in the study area were recorded using a Global Positioning System (GPS) receiver (i.e. TRIMBLE Geo XT). The vegetation surveys were conducted between February and April 2018. Both the GPS points and surveyed vegetation data were partitioned into 70% (N = 32 samples): 30% (N = 25 samples) respectively for training and test datasets (Mutanga, et al., 2012). The training datasets were used to calibrate SPOT-6 derived vegetation index (i.e. NDVI) for estimation of above ground vegetation canopy values. The test data was used to evaluate the accuracy of the output above ground vegetation map.

3.3.3. Normalized Difference Vegetation Index (NDVI)

The Normalized Differential Vegetation Index (NDVI) was calculated using the Image Analysis Window in ArcMap10.4 software version and spectral intensity of vegetation signal differences and non-vegetated surfaces were studied before carrying out a simple linear regression analysis. The NDVI values range from -1 for non-vegetated features space to +1 for photosynthetic or active green vegetation cover (Tucker and Sellers, 1986). Therefore, the computation of the NDVI allowed the researcher to discriminate vegetation cover types in the study area. As shown in Figure 3.3, SPOT-6 image has one near-infrared band (NIR: 0.76-0.89 μm) and a Red (0.62-0.69 μm) band. These two bands were used to calculate NDVI (Equation 3.1):

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Equation 3.1

Next, image values corresponding to the GPS locations of field-based vegetation survey data were extracted using the Zonal Statistics as Table function in the Spatial

Analyst extension of ArcGIS 10.4 Software. A Simple linear regression analysis was carried out to obtain regression coefficients for the NDVI layer.

$$Y = \beta X + b \qquad \textbf{Equation 3.2}$$

Equation 3.2 is the model behind the simple linear regression used to explain the relationship between vegetation canopy cover as the outcome and the NDVI layer as the explanatory or independent/predictor variable. The model assumes that values between the observed and the explanatory variables can be possibly represented by values of the explanatory variables. Equation 3.2 represents Y as the outcome of the canopy (%), and X represents the input NDVI as the explanatory variable. Therefore, any expected value of Y is estimated given X, constrained to some beta value coefficient of β, and b is the constant parameter estimate of the regression slope used to predict an expected value, Y for canopy cover. Once these coefficients were established, the values were used in the Raster Calculation function to convert the NDVI values into above ground vegetation estimation which is expressed as % of canopy cover.

3.3.4. Image fusion

Image fusion was carried out using Pan-sharpening workflow in ENVI software Version 5.3. Pan-sharpening is a process of combining high-resolution panchromatic image band with lower resolution multispectral bands. The resultant data is an improved high-resolution colour image. For this research, the pan-sharpened image product only served to aid visual interpretation of topographic land features on the image. No further spectral analysis was performed on the image. Figure 3.4 shows the output of combining high spatial resolution (1.5 m) panchromatic with a lower spatial resolution (6 m) multispectral bands of SPOT-6.

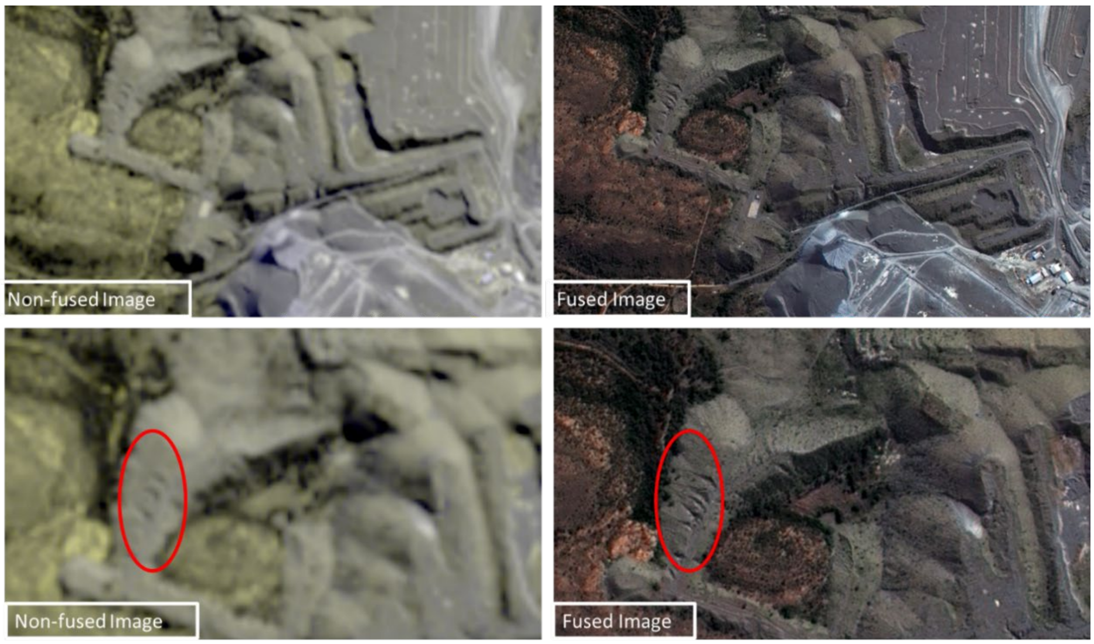

Figure 3.4 Pan-sharpened SPOT-6 (1.5 m) image (Right panels: Non-fused) with an improved resolution image compared with 6m–multispectral image (Left-hand panels) for better interpretation of tailings erosion highlighted in red oval shapes.

3.4. Model validation and accuracy assessment

The Root Mean Square Error (RMSE) was implemented to compare the predicted values and on the ground measured above ground vegetation canopy cover and the NDVI-based estimated vegetation cover. The RMSE is known as the Root Mean Square Deviation between predicted and observed values. It is one of the most widely used statistical tests in the field of geographic information sciences (McCoy, 2006). The RMSE was calculated in excel using Equation 3.3, whereby $\mathbf{P_i}$ and $\mathbf{O_i}$ are predicted and observed values, respectively and **n** is the sample size.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{n}}$$

Equation 3.3

The generation error between the input DEMs and output DEM was also estimated using the ground reference dataset collected using the GPS device. The RMSE equation was used to compare the reference GPS points deemed to be of higher accuracy with the output DEM (Wechsler, 2007). In the case of applying the RMSE to assess DEM dataset, the estimated elevation grid cell values and the corresponding reference elevation value at grid location x and y coordinates, against the number of residuals.

CHAPTER 4: RESULTS

The integration of GIS and remote sensing data for monitoring vegetation on topographically varying landscapes has increasingly become a common technique. For the current research, data analyses techniques consisting of GIS and remote sensing approaches were implemented to aid field-based observations on the influence of topographic variables on vegetation establishment. Section 4.1 presents results of DEMs fusion analysis for the creation of a more accurate DEM. Section 4.2 presents the results generation of slope derivates. Section 4.3 consist of the results of multispectral SPOT-6 image data analysis for calculating commonly used NDVI index and assessment of vegetation canopy cover on some mine tailings and hillslopes. Finally, Section 4.4 presents the results of the relationship between vegetation cover and derivates of slope in the study area.

4.1. Visual interpretation and accuracy of generated DEM

The DEM fusion analysis (Section 3.1.2) consisted resampling of lower resolution 30m SRTM DEM and then fusion with the 5m higher resolution DEM (cdDEM-5m) data acquired from CD-NGI. Figure 4.1 shows the input SRTM (Panel A) and cdDEM-5m (Panel B) DEMs. The fusion process allowed the different grid resolution DEMs to be assessed so that notable gaps in the input DEMs were filed with on the ground reference elevation data (Figure 4.1, Panel C). In addition, Panel C of Figure 4.1 shows the final output from the fusion process whereby resampled 5m grid cells SRTM and the cdDEM-5m DEMs were combined to produce a higher accuracy, topographically enhanced DEM for further analysis. Hillshading effect was applied to all data layers to enhance the representation of the hillslopes and other surfaces.

Visual interpretation of the DEMs reviewed that, there existed varying degrees of obvious enhancement in the output DEMs containing more systematic values compared to the reference elevation values, with an RMSE of 5.75 m, which is 39% and 14% lower than that of SRTM 30 m and cdDEM5m respectively. The RMSE value for SRTM 30 and the cdDEM5m were obtained from the metadata that accompanied the input datasets.

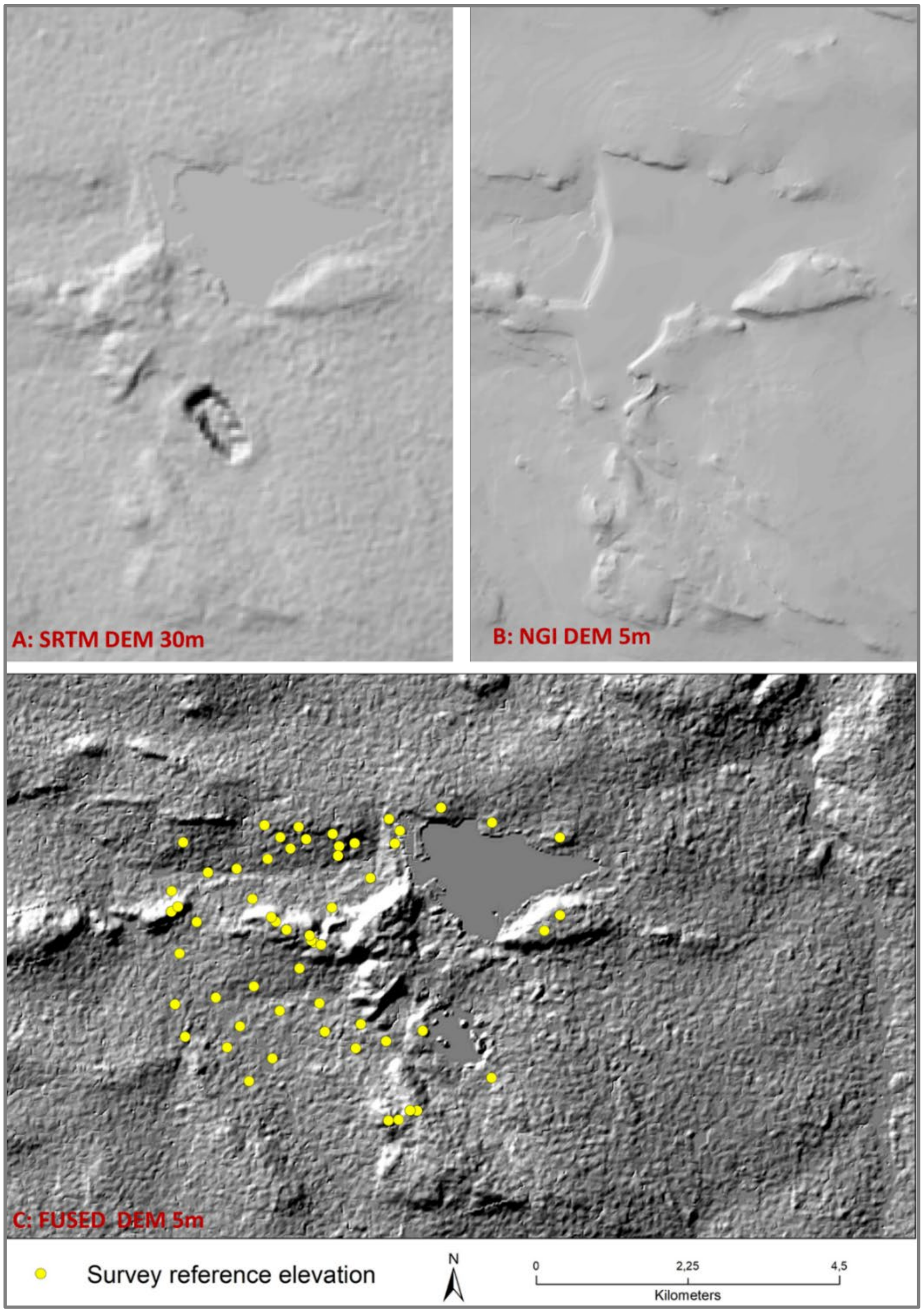

Figure 4.1 Input DEMs: SRTM (A) and cdDEM-5m (B) and final output fused DEM.

4.2. Derivates of slope

4.2.1. Slope classification

The slope is classified using an interval of 5 from 0 to 35 % and then greater than 35%. Figure 4.2 shows the map of slope classification in the study area. Results indicate the slope value for most DEM grid cells are between 10% and 15%. Moreover, there is notable variation in the slope projection on the land surface. Such a noticeable variation in slope, together with orientation or aspect of the different slope is important for the analysis of vegetation canopy in relation to the projection of tailings and hillslopes under investigation in the study area.

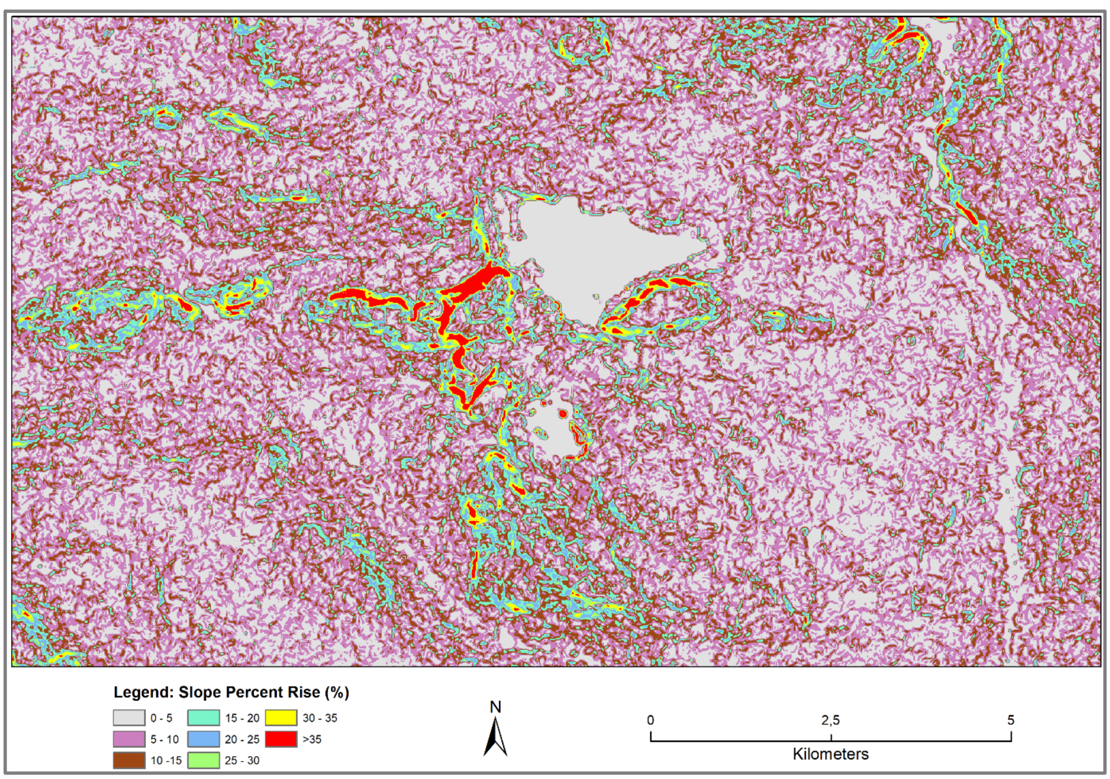

Figure 4.2Slope classification map

4.2.2. Second derivates of slope and erosion

Analysis of topographic site exposure resulted in SEI values ranging from -51 to 46. The resultant SEI values show the current research area consists of moderately cool to moderately warm locations. The result further shows that there can be a significant degree of surface exposure to wind erosion. Figure 4.3 is surface exposure index information output based on the analysis of 5m high-resolution DEM (Section 3.2.2).

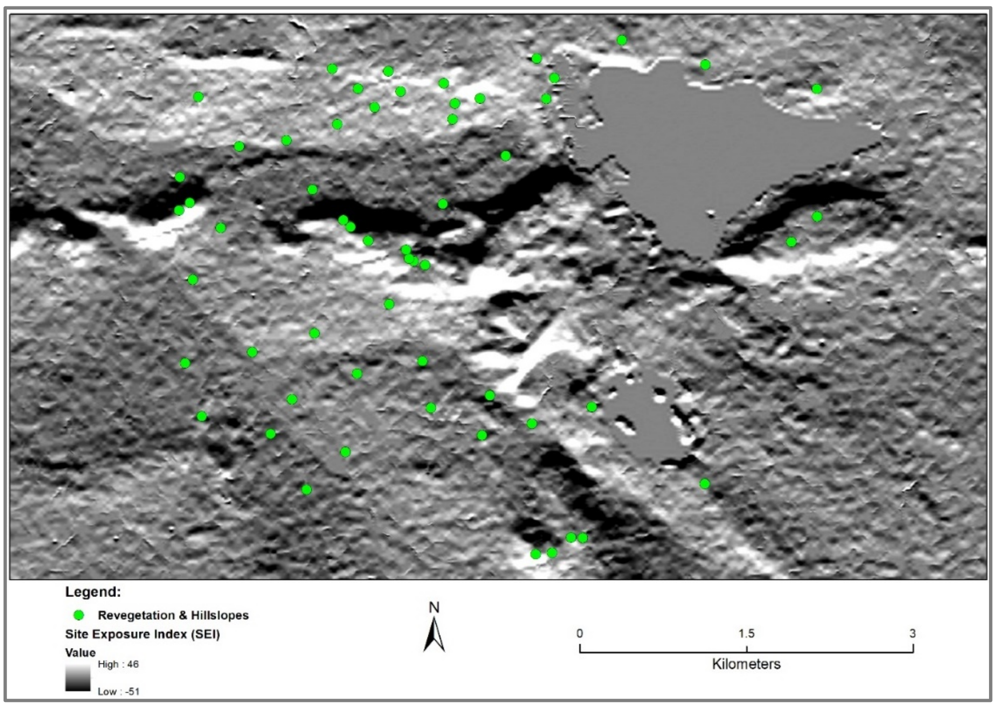

Figure 4.3 Map of site exposure index.

Slope steepness and orientation values were combined to derive three kinds of surface curvature for the study area (Section 3.2.3). Figure 4.4 to 4.6 show results for the modelled surface curvatures representing the profile, platform, and standard curvature types, respectively.

Figure 4.4 Profile curvature and above ground vegetation canopy survey locations.

Figure 4.5 Platform slope curvature and above ground vegetation canopy survey locations.

Figure 4.6 Standard slope curvature and above ground vegetation canopy survey locations.

4.3. Above ground vegetation canopy estimation

In order to assess the status of revegetation activities, researchers, land managers and environmental practitioners increasingly employ modern geospatial data techniques to derive vegetation estimates. Moreover, the accurate estimation of vegetation condition regarding ground cover is important for evaluating the success of rehabilitation efforts at any given time. The vegetation canopy estimation followed the preparation of SPOT-6 data, calculation of NDVI (Figure 4.7, Panel A) and integration of field survey and NDVI to output map of vegetation cover in the study area. The result indicates above ground vegetation canopy cover that ranged from no-cover with a pixel value of 0 to the highest cover of 70.6% (Figure 4.7, Panel B).

The simple regression model implemented to estimate vegetation cover yielded a high predictive capacity with a regression coefficient of $R^2 = 0.78$ (Figure 4.8, Panel A) for the model calibration dataset. Consequently, the predicted and observed values yielded an $R^2 = 0.72$ (Figure 4.8, Panel B) with an RMSE of 8.87% above ground vegetation canopy cover calculated based on the test dataset.

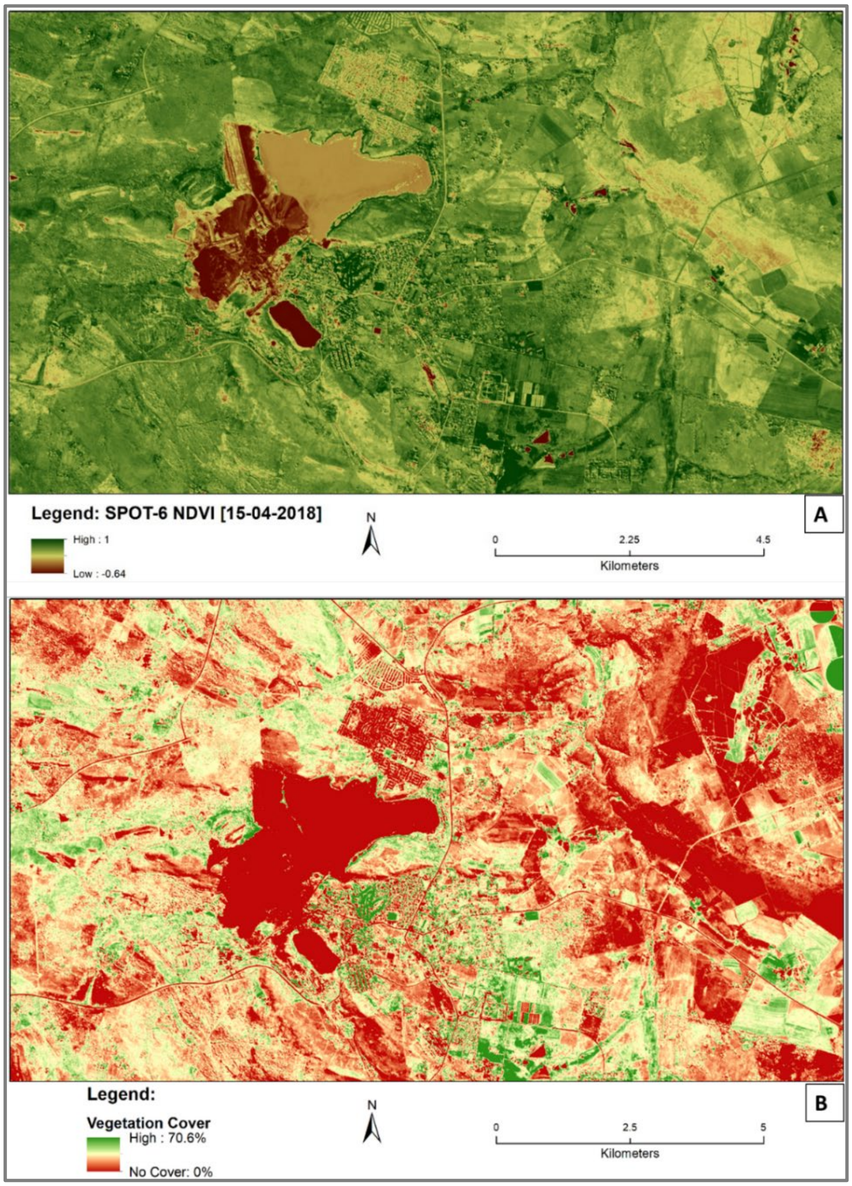

Figure 4.7 The SPOT-6 derived NDVI image (A) and above ground vegetation canopy cover (B)

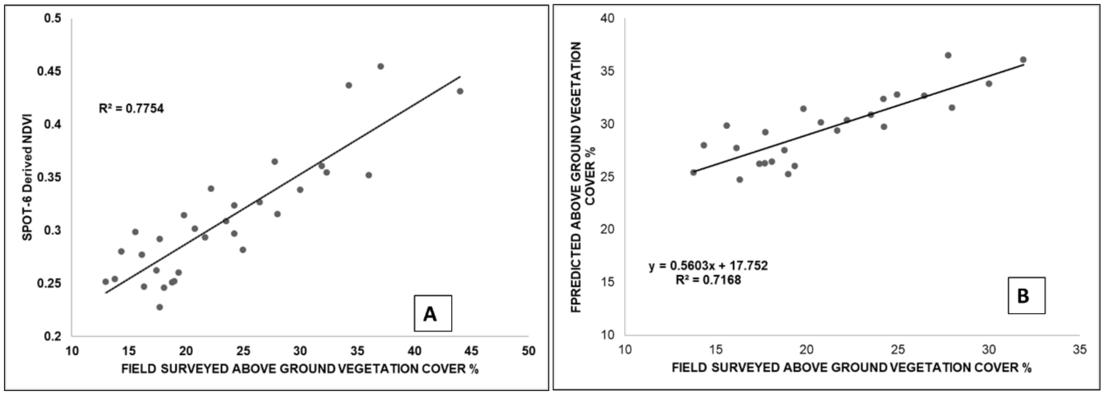

Figure 4.8 Predictive capacity of NDVI (Panel A) and observed vs predicted above-ground canopy cover (Panel B).

4.4. Above-ground vegetation cover and topographic variables

Table 4.1 shows descriptive statistics of derived datasets used for all analysis. The spatial variation of NDVI along elevational gradients in the study area was assessed. The result shows that NDVI values inversely relate to the elevation in the area (Figure 4.9, Panel A). The resultant relationship between NDVI and elevation provides an import insight into understanding vegetation spectral response, characterized by remote sensing derived NDVI. The NDVI layer was modelled to quantitatively estimate above ground vegetation canopy cover and then relate the output map against slope map (Section 3.2.1). Correspondingly to the NDVI vs Elevation relationship, Figure 4.9 (Panel B) shows an inverse statistical variant in above ground vegetation canopy cover against the degree of change in slope across the surveyed sites. In addition, relationships between above ground vegetation canopy cover and second derivates of slope (Appendix 1: SEI and three surface curvatures – Profile, Platform and Standard Curvature variables) were analyzed.

The results show that the pattern of erosion on the mine tailing and nearby hillslopes is a combination of these slopes derivates, therefore, exposing the study area to erosion agents such as wind and rainwater (Al-Aklabi, et al., 2016).

Table 4.1 Descriptive statistics of input data and derived variables

Variables	***Min***	***Max***	***Ave***	***STD***
AGV (%)	12.98	44	22.43	6.63
NDVI	0.23	0.46	0.30	0.05
Altitude (m)	1306	1484	1381.84	54.21
Slope (%)	2.98	27.06	13.11	6.91
Site Exposure Index (SEI)	-13.63	10.28	0.50	4.89
Profile curvature	-1.71	5.66	0.46	1.31
Planform curvature	-6.44	2.59	-0.45	1.62
Standard curvature	-12.09	4.30	-0.90	2.86

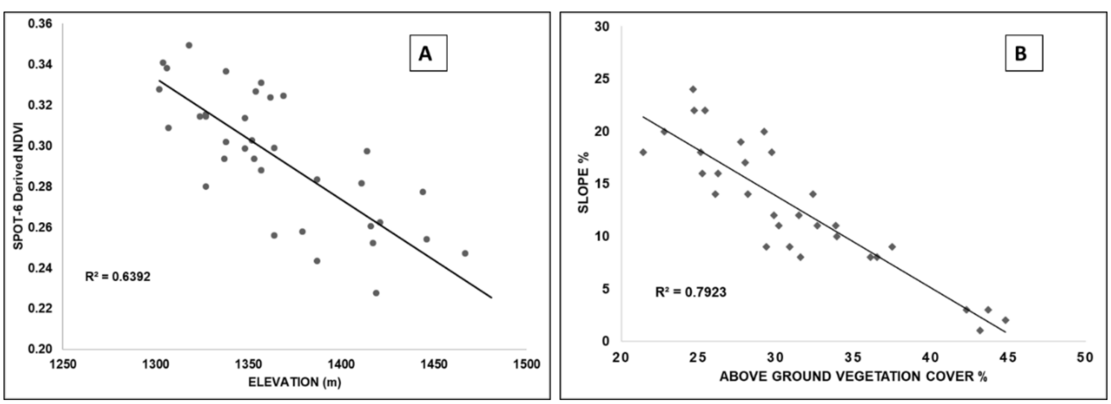

Figure 4.9 Relationship between topographic elements and vegetation.

CHAPTER 5: DISCUSSION AND CONCLUSIONS

The discussions of study results are in four interrelated sections. Section 5.1 discusses the results of DEM data fusion and generation of selected slope derivates. Section 5.2 discusses results of integrating remotely sensed SPOT-6 NDVI and survey data for estimation of above ground vegetation cover on both tailings and hillslopes in the area under investigation. Next, Section 5.3 discusses slope and elevation thresholds on the Vetiver System application for revegetation of tailing slopes in the study area. Finally, Section 5.4 provides conclusions and recommendations.

5.1. DEM Fusion and slope derivates

Nowadays the process of fusing DEMs of different resolutions to produce an output one which is more accurate can be regarded as a common practice. However, the reported accuracies indicate that different DEM fusion methods have yielded inconsistent results (Ugur, et al., 2018). In the current study, the fusion of multisource DEMs to generate a higher resolution and more accurate DEM was studied. The objective was to combine the SRTM 30 m and high-resolution CD-NGI 5 m DEMs, with the aid of on the ground reference elevation dataset. The results obtained suggest that vertical and horizontal accuracies of SRTM 30 m DEM could be improved by integration with the high spatial resolution cdDEM5m, combined with on the ground reference elevation dataset. With the SRTM DEM data, it has been widely reported in the literature that vertical accuracy can be impacted by a low amount of RADAR backscatter (Elkhrachy, 2017).

The land surface features that impact the backscatter values are referred to as target parameters. These parameters include targets such as the soil moisture; vegetation structure (height, density and coverage); irregular orientation of the surface roughness due to tailing pile (Reda & Nagar, 2017; Al-Aklabi, et al., 2016). Therefore, it is not surprising that in the current investigation, mine tailings slope grids were the pixels that needed updating with on the ground reference GPS elevation points. Such an observation is important for investigation focused on surveying and mapping topographic features base single time snap DEM generated from remotely sensed observations.

The current research provided important insights into understanding the influence of anthropogenic topographical signatures in specific locations on the landscape. The study also demonstrated that topographic signatures due to changes in mine tailing plies can be innovatively modelled based on the combinations of multisource input elevation data. Interestingly, the increased availability of free global DEM datasets with sufficient vertical accuracies provides the opportunity for DEM fusion studies. Thus, results from the current study offer a platform for generating low-cost, DEM of better accuracy in environmental applications. The main challenge is the ability of researchers to identify the most suitable fusion model applicable to anthropogenic topographical landscapes.

Cooperation of mine managers in providing adequate access to researchers to conduct on the ground or field surveys might allow the upscaling of the investigation into fusion techniques processes from the scientific to the practical application in the real-world settings. Previous researchers (Haupt, 2018; Hawker, et al., 2018) demonstrated the contributions and usefulness of fusion techniques in generating high-resolution DEMs for landscape studies. The experimental results in the current study confirm that significant improvements can be achieved in updating existing DEMs through the fusion of the temporal and spatial appestats of existing DEMs. Moreover, the combination of DEM fusion processes and capabilities of optical image data analysis has enabled accurate visual interpretation and processing inputs image data for quantification of vegetation cover with improved spatial and topographic accuracies.

5.2. Vegetation cover and topography

Changing in topographic variables have widely been reported to affect fine-scale variations in vegetation structure and composition. The results of the current study suggest that topography elements are important factors in revegetation on the anthropogenic topographical varying landscape (Figure 4.9). In particular, the increase in cover vegetation of tailings and hillslopes subjected the Vetiver grass was substantial. However, the vegetation cover establishment under the Vetiver System is somehow influenced by the topographic slope curvature and the surface exposure index. Previous studies found that the composition of vegetation on random varying topographic landscapes was influenced by the nature of the slope curvature and extent of the site exposure (Pennock & De Jong, 1987; Tarolli & Giulia, 2016). For the current research, the factors important for the vegetation establishment on slopes are likely to be the elevation and slope derivates assessed. However, given the relatively small number of residuals or samples, further studies may be warranted to support the results of this research.

5.3. Thresholding of slope and the Vetiver System

The exposure and subsequent transportation of mine tailing materials downslope can be seen as a form of surface erosion that mechanically moves materials, due to gravity, along with the slopes of mine tailings (Tarolli & Giulia, 2016). Moreover, mine tailing can accelerate the erosion process whereby large quantities of sediment are exposed and therefore transported downslope by rain-water and wind. In that regard, the use of vegetation cover as a bioremediation technique to prevent surface erosion can be seen as obvious. However, there is insufficient understanding in the literature on the extent to which anthropogenic topographical elements affect the application of revegetation techniques such as the Vetiver System.

The experimental results from the current research show that increased heterogeneity in surface topography due to mine tailings possibly have been significantly impacted the vegetation establishment. The current research followed both qualitative and quantitative approaches to measure the topographic influences on revegetation of some mine tailings and hillslopes in the Cullinan study area.

5.4. Conclusions and Recommendations

The outcomes of the current research have provided useful insights into the interpretation of the output maps. The geomorphic or topographic thresholds of the Vetiver System for establishing vegetation cover and erosion control on slopes of tailings have been proposed. The methodology implemented for DEM fusion introduced a spatial framework for studying the topographic thresholds of the Vetiver System in mine tailing slopes revegetation activities.

Next, the current research has demonstrated a way to estimate above ground vegetation canopy cover for making inferences on the topographic thresholds of the Vetiver System. The input DEMs with prior information was useful for evaluation of the data fusion processes investigated. The research provided experimental evidence of improving operational DEMs based on data fusion technique. Future studies are warranted to devise strategies that take advantage of some complementary technologies such are remotely operated instrumentation for collection of elevation data.

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APPENDICES

Appendix 1

Altitude	NDVI	AGV	Slope	Aspect	Planform Curvature	Profile Curvature	Standard Curvature	SEI
1357.00	0.33	17.70	10.67	258.80	1.35	-0.19	1.54	0.27
1331.00	0.27	18.09	14.22	189.91	0.26	0.42	-0.15	2.21
1348.00	0.18	16.32	9.17	143.57	-0.08	0.24	-0.32	6.46
1348.00	0.30	18.77	5.11	235.28	0.13	0.14	0.00	-5.03
1354.00	0.33	18.98	14.95	321.90	0.18	-0.14	0.32	-6.04
1327.00	0.31	13.77	24.04	97.14	0.05	-0.27	0.32	-4.59
1338.00	0.30	19.34	10.78	227.00	-0.10	0.40	-0.50	3.83
1383.00	0.45	17.40	8.23	301.17	2.59	-1.71	4.30	-9.02
1414.00	0.23	16.13	6.43	156.75	-2.88	2.21	-5.09	4.55
1337.00	0.29	14.33	4.49	131.59	0.13	-0.09	0.23	6.08
1352.00	0.36	24.95	23.94	122.39	0.32	0.22	0.10	7.76
1364.00	0.26	17.71	31.67	107.06	-3.86	1.56	-5.42	6.81
1348.00	0.31	21.67	13.52	191.28	-4.58	1.71	-6.28	4.87
1379.00	0.26	24.24	0.28	224.32	0.27	0.14	0.13	6.06
1353.00	0.29	15.58	6.26	109.45	-3.07	0.86	-3.93	4.98
1327.00	0.32	20.78	9.80	117.94	0.11	-0.20	0.30	4.11
1338.00	0.25	23.52	11.67	94.62	0.13	0.11	0.02	-0.06
1336.00	0.37	19.80	9.34	69.95	-0.11	0.37	-0.48	-0.68
1327.00	0.28	27.99	15.39	298.39	-0.03	0.17	-0.20	-0.90
1318.00	0.35	24.22	20.00	126.95	-0.80	1.29	-2.09	-0.45
1307.00	0.31	26.47	16.47	196.90	0.21	-0.11	0.32	-4.61
1324.00	0.31	30.00	14.24	336.11	-0.35	0.11	-0.45	-2.71
1369.00	0.32	22.20	15.42	351.57	0.91	-0.38	1.29	-13.63
1304.00	0.34	31.91	27.06	294.20	0.25	-0.07	0.32	-0.56
1302.00	0.33	27.77	5.58	200.19	-0.08	0.13	-0.21	-1.22
1306.00	0.34	15.58	20.42	171.55	-0.02	0.28	-0.30	0.12
1323.00	0.37	26.47	21.91	131.95	-0.16	-0.06	-0.10	7.76
1421.00	0.26	19.80	25.39	146.52	-2.38	2.10	-4.49	2.76
1411.00	0.28	20.78	17.99	64.06	-0.03	0.25	-0.28	-4.15
1416.00	0.26	37.06	8.65	347.99	-0.08	-0.03	-0.05	-4.38
1362.00	0.32	36.00	14.32	217.63	-4.07	4.33	-8.40	6.41
1338.00	0.34	21.67	5.14	184.99	-0.03	0.53	-0.56	7.87
1342.00	0.38	31.91	0.89	230.10	0.15	-0.10	0.25	3.09
1348.00	0.20	27.99	4.33	337.58	0.02	0.11	-0.09	-3.39
1387.00	0.28	18.77	8.77	304.78	-0.18	0.70	-0.88	-8.39
1364.00	0.30	32.32	27.24	109.99	-0.15	0.18	-0.33	2.24
1352.00	0.30	14.33	2.98	277.48	-6.44	5.66	-12.09	-0.73
1417.00	0.21	23.52	8.98	23.17	0.23	-0.15	0.38	-1.12
1417.00	0.25	44.00	14.24	50.58	1.60	-1.64	3.24	0.13

1414.00	0.30	30.00	6.02	38.78	-0.61	0.24	-0.85	-6.42
1348.00	0.10	34.24	17.77	257.03	-0.15	0.41	-0.56	-4.68
1338.00	0.37	17.40	2.91	196.21	-5.14	5.49	-10.63	8.42
1402.00	0.11	24.95	12.96	246.93	0.01	0.36	-0.34	1.09
1414.00	0.05	19.34	9.62	302.81	0.02	0.10	-0.08	-4.00
1398.00	0.11	24.22	9.70	224.13	-0.05	-0.31	0.25	3.94
1419.00	0.23	12.98	6.13	141.49	0.28	0.33	-0.05	-1.80
1444.00	0.28	18.98	3.34	201.09	0.12	0.26	-0.15	2.71
1437.00	0.32	24.24	7.71	245.61	0.04	0.36	-0.32	1.94
1479.00	0.29	27.77	17.27	51.57	0.27	-0.27	0.54	-2.56
1486.00	0.25	17.70	25.81	291.88	0.00	0.14	-0.14	-3.65
1481.00	0.20	16.13	1.82	224.73	-0.26	-0.09	-0.17	10.28
1387.00	0.24	17.71	3.77	299.51	-1.31	1.04	-2.34	-1.34
1446.00	0.25	13.77	8.09	168.06	1.16	-1.12	2.28	2.11
1484.00	0.25	18.09	10.20	49.88	0.28	0.17	0.11	-3.14
1461.00	0.34	22.20	2.90	152.80	0.12	-0.52	0.64	5.18
1357.00	0.29	16.32	6.32	256.34	0.15	-0.39	0.54	-0.31
1467.00	0.25	20.85	27.24	223.40	0.17	0.79	-0.62	3.82