The Use of Remote Sensing to Map Landslide Prone Areas in Makhado Municipality of Limpopo Province, South Africa

B.D.O. Odhiambo, M.O. Kataka and Muhuma Mashudu

University of Venda, School of Environmental Sciences, Private Bag X5050,

Thohoyandou, 0950, Limpopo, South Africa

Introduction

Landslides can assume catastrophic and disastrous proportions causing immeasurable damage to life and property, and are one of the costliest natural hazards. They belong to a class of geological phenomena that occur very rapidly. The term landslide describes a wide range of processes responsible for the downward and outward movement of slope forming material composed of rock, soil, artificial fills or a combination of all these down a slope (Huabin *et al.*, 2005). Landslides can seriously injure or even kill people and damage property. Studying the risks which are caused by landslides is important in the context of its forecasting.

The causes of landslides can either be natural or human related (Tanya, 2001). Economic loses and casualties which occur because of landslides in many countries (Ercanoglu *et al.* (2004) are greater than commonly recognised. This situation is more deplorable in developing countries, which are comparatively less equipped technically and financially to deal with natural hazards when they occur (Diko, 2012; Ngole, Ekosse and Ayonghe, 2007).

A brief review of some of the more prominent and tragic landslide events in recent times around the world shows that by comparison the landslide hazard level and frequency over much of South Africa is relatively low. This is largely a consequence of a low overall seismic and tectonic hazard regime compared to other locations such as Indonesia, California, Peru, Japan, China, Turkey and Pakistan, where such geohazards are major triggering factor of mass movements. Some examples of devastating landslides which have occurred at global level include the 1972 Calabria landslide in Italy and the 1985 Armero landslide in Colombia (Alexander, 1993). Woldearegay (2017) documented occurrence of major mass-movements, including landslides, in Sub-Sahara Africa. At the time of going to press (1 October, 2018), a 7.5 magnitude Earthquake in Indonesia triggered a massive landslide which has become one of the most devastating landslides recorded. The 2018 Earthquake caused liquefaction of the soil leading to subsidence and massive destruction of property, lives and infrastructure in the Indonesian Island of Sulawesi.

Globally, landslide hazards cause billions of dollars in damages and thousands of deaths and injuries. Japan leads other nations in landslide severity with projected direct and indirect losses of four billion dollars annually. The United States of America, Italy and Canada follow with the cost of damage ranging from one to two billion dollars and between 25 to 50 deaths annually (National Disaster Education Coalition, 1999:93). Landslide hazards are also common in developing countries where their economic losses sometimes equal or exceed the gross domestic product (GDP) of the country (Sassa, *et al.*, 2005:135). Huabin, *et al.*, (2005) estimated that in 1998 alone 180,000 avalanches, landslides, and debris flows of different magnitudes occurred in China, causing an estimated direct economic loss worth 3 billion dollars.

In the less developed countries, natural hazards are progressively striking unprecedented impacts on human lives, property, livelihoods, assets and infrastructure utilities globally (Sutanta *et al.*, 2013). The needy, marginalized groups and those located in hazardous areas (Davies *et al.*, 2009) are the most vulnerable to the devastating effects of natural hazards. This results either from the lack of economic, social, physical and environmental resources which can enable them to initiate some alternative strategies or lack of hazard risk management strategies that could improve their capacity to withstand the impacts of natural hazards (Wisner *et al.*, 2003).

In South Africa, despite significant strides made towards consolidating data on geohazards in the country, very few studies on mass movement have been documented (Singh *et al*., 2008). Examples include the Mount Curie debris in Kokstad, KwaZulu-Natal, the Lake Fundudzi Paleo-landslide in Limpopo Province and the Ukhahlamba-Drankensburg foot slope landslide in Kwazulu-Natal (Singh et al., 2008). In Limpopo Province, apart from the Lake Fundudzi landslide, no other study has been documented. In South Africa, landslides have been responsible for fatalities on the Chapman's Peak drive along the Cape Peninsula on the Atlantic coastline, prompting extensive structural improvements and removal of loose rock from the steep slopes. The catastrophic failure of a mine tailings in Merriespruit, a suburb in Virginia in the Free State Goldfields, was initiated by heavy rainfall in February 1994. The Merriespruit mud flow devastated the residential suburb resulting in the death of seventeen people. The hazard prompted a review of the Mine Health and Safety legislation and an introduction of a new Code of Practice in 1997. Many areas in eastern South Africa are prone to slope failure due to diverse morphology of the terrain that comprise of high mountains and steep valley slopes. The region experiences high intensity summer rainfall, has deep weathering associated with the humid climate and ancient land surface remnants, combined with a range of geological and structural influences. The study area is geographically located in this eastern region of South Africa.

The Study Area

Khalavha Village is approximately 26 km from Thohoyandou town in Limpopo Province. It is geographically bound by latitude 22˚ 54' 55"S and 22˚54' 58"S, longitude 30˚17' 30"E and 30˚ 20' 39"E.

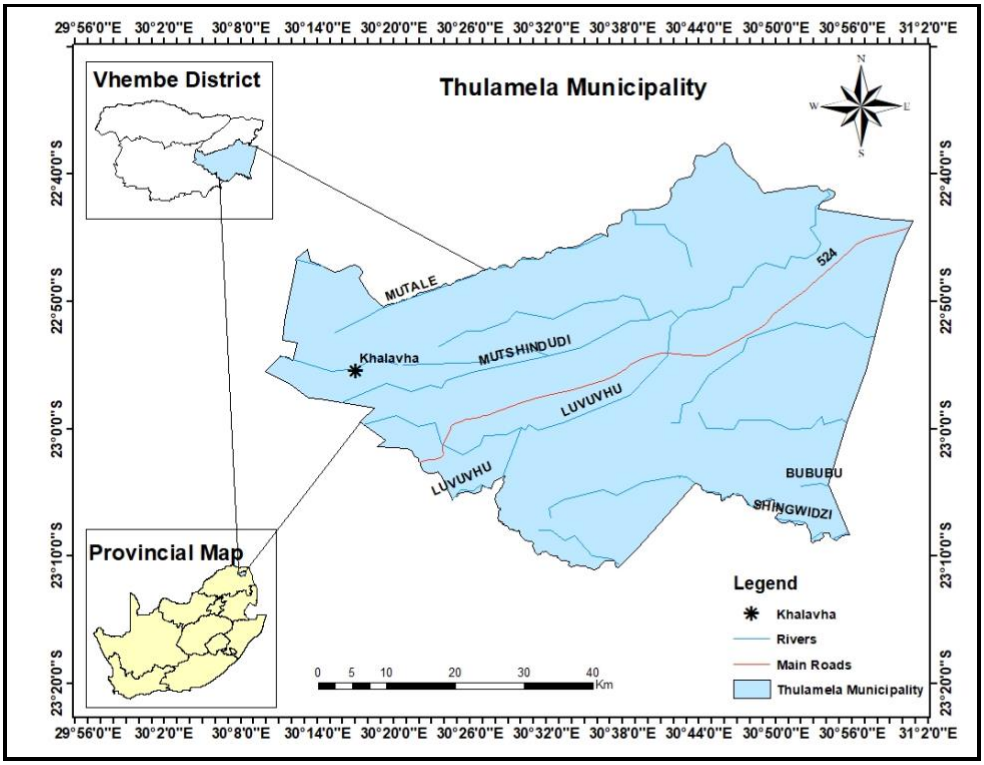


Figure 1: Location of the Study Area in Vhembe District Municipality, Limpopo Province.

The area is located within the Soutpansberg mountain range which is a section of the Drakensberg Mountains. The general relief elevation is about 1,500m high above the sea level. The area which has a small summit, steep slopes and a local relief amplitude of about 300m. Climate is humid, and has a mean annual rainfall that ranges from 755mm to 798mm. The mean maximum daily temperature over the area ranges between 30°C and 40°C during summer with a low between 22°C and 26°C in winter. Mean minimum daily temperature ranges from 18°C to 22°C in summer and varies from 5°C to 10°C in winter. Subsistence farming is the main agricultural activity undertaken in the study area. The main crops types include maize and horticultural crops like cabbage, tomatoes, onions, and other green vegetables.

Classification and Factors that Trigger Landslides

Factors that directly and indirectly affect slope stability and are responsible for the occurrence of landslides include lithology, structure, soil depth and texture, geomorphology, amount of slope and slope angle. Weathering, land use and cover type are important anthropogenic activities (Singh, 2010). Normally, slope stability depends on the combined effect of all these factors (Pande *et al.*, 2009). In 1978, Varnes classified landslides based on material type and type of movement associated with a landslide. This classification system has been widely used and accepted in landslide studies. In Varnes' Classification, material type includes rock, earth, soil, mud and debris; while the kinematically distinct types of movement are fall, topple, slide, spread and flow. When type of material and movement are combined classifications such as debris flow, rock fall, earth slide, landslide can be described (Varnes, 1978). Table 1 which shows types of landslides, is adopted from Smith (2001). This classification basically recognises the categories depicted in Varnes' Classification, but adds speed to type of movement.

Influence of Slope

Relief is a principal factor that determines the intensity and character of landslides. Relative relief is an index of topographic variation (Schulze and Horan, 2007) that is normally referred to as the relief amplitude of an area. Thus, landslides are mostly associated with mountain ranges that have high relative relief, are rugged and steep. Much of the central

Table 1: Types of Landslides, their characteristics and movement type.

Type of Landslide	Character or nature of movement	Subdivision	Speed and type of movement
Falls	Particles fall from Cliff and accumulate at base.	Rock falls	Extremely rapid, develops in Rocks.
		Soil fall	Extremely rapid, develops in sediments
Slides	Masses of rock or sediments slide down slope along planer	Rock slide (Translational)	Rapid to very rapid sliding of rock mass along a rectilinear or inclined surface

	Surface.	Slump	Extremely slow to moderate
		(Rotational)	sliding of sediment rocks
			mass along a curved surface
Flows	Displaced mass flows	Solifluction	Very slow to slow movement
	as plastic or viscous		of saturated regolith as
	Liquid.		lobate grows
		Mudflow	Very slow to rapid movement
			of fine grained particles
			with 30% water.
		Debris flow	Very rapid flow of debris;
			commonly started as
			a slump in the upslope area
		Debris	Extremely rapid flow; fall
		avalanche	and sliding rock debris
Creeping	Regolith soil and rock.		Extremely slow superficial
			deposit and the influence
			of gravity; predominantly
			seasonal
Complex	Combination of two or more principle types of movements.		

Adapted and modified from Smith, (2001)

region of South Africa is of high elevation, undulating plain with low moderate relief. The direct influences include slope steepness, river valley morphology and thawed gradients.

Slope angle is the most important relief characteristics that affects the mechanism and the intensity of the landslides. The greater the slope angle and convexity of the slope, the greater the number of the landslides. The stability of the slope against sliding can be defined by the relationship between shear forces and the resistance to shear.
Gravity is the main force responsible for mass wasting (UNESCO/UNEP, 1988). On slopes, the force of gravity can be resolved using two components, the one acting perpendicular to the slope and the other one acting tangential to the slope, this is an important factor in the distribution of landslides and mass movement which only occur when the critical angle is exceeded.

Influence of Geology

Geology greatly influences the occurrence of landslides since different rock types exhibit the varying resistance to weathering and soil erosion. The attitude (dip and strike) of the stratigraphic sequence, abrupt changes in the lithological characteristics and occurrence of bedding planes have strong influence on the strength characteristics of a rock mass. High possibility of failure exists in over-dipping slopes where bedding planes appear on the topographic surface.

Interbedded shales and sandstones are normally more susceptible to failure, because the coarser units transmit water more readily to the weaker and less permeable beds. This results in a rise of pore water pressure and loss of shear strength, and leads to slope failure. Lithological variations of rock masses are important when determining the shear strength, permeability, susceptibility to chemical and physical weathering, and other characteristics of soil and rock material, which in turn affect the slope stability. For example, soft rocks such as mudstones, tillites, phyllites and slates are generally more susceptible to landslides than hard and massive rock types like granite and metamorphosed limestone.

Influence of Soil Characteristics

The balance between soil forming processes and soil erosion is depicted by the depth of soil. The soil profile controls the tolerance of a slope to all destabilising factors. Inclination and orientation of structural surface have the greatest effect on the stability of the slopes (Crozier, 1986). Soil texture determines its ability to absorb and store water, generally this is referred to as liquefaction, a condition when the soil momentarily liquefies and tends to behave as dense liquid a condition which is required for landslides to occur. Sand and silts or a combination of both are the most important textures that control liquefaction (Bryant, 1991; Msilimba, 2002; Msilimba and Holmes, 2005). Soils such as silt and clay are weaker and they have complex (colloids) or multiple planes of weakness (clay-humus complex) in common which increase the occurrence of landslides. Soils with high clay content are known to swell when it is wet and shrink in dry weather (Krhoda, 2013).

Influence of Snowmelt

In many cold mountain areas snow accumulates during winter and melts in summer. Snowmelt can be a key to onset of landslides. This is especially significant with sudden increases in temperature which leads to rapid melting of snow. The melt water infiltrate into the ground, which may have impermeable layers below the surface due to still soil or rock leading to rapid increase in pore water pressure, and resultant landslide activity. This effect can be especially serious when the warmer weather is accompanied by precipitation, which both adds to the ground water and accelerates the rate of thawing. Melting snow seeping into disintegrating rock is reported to be responsible for a massive landslide that killed 83 people in a mining area near Lhasa, the Tibet Autonomous Region on 29 March 2013 (China Daily, 6th April 2013).

Influence of Rainfall

Prolonged high intensity precipitation often trigger landslides (van Schalkwyk and Thomas, 1991). In South Africa, the heavy rain of September 1987, February 1988 in KwaZulu-Natal and after the high intensity rains of February 2000, several slope failures observed and serve as suitable examples. The unusual rains that resulted from the Eline and Gloria tropical cyclones damaged roads, bridges and public and private properties and 101 people died (Limpopo Provincial Disaster Management Unit, 2000).

During periods of prolonged rainfall changes in moisture content of the regolith or rock on a hill slope adversely affects slope stability. An increase in pore water pressure increases the weight and gravitational force acting on slopes. Further, saturation of soil also reduces cohesion and friction between grains, and increased moisture also reduces friction along zones of weakness in the bedrock and soil interfaces, causing material above to slide along the lubricated bedding plane.

Influence of Anthropogenic Activities

Human activities increase the frequency of landslides and rockslides due to undercutting for roads and railroad excavations (Scharpe, 1938). Today, these anthropogenic activities are still the major factors that cause slope failures (UNESCO/UNEP, 1988). For example, landslides are easily triggered by removal of lateral support that causes slope failure especially in the development of roads cuts, construction of houses and foot paths.

Objectives of the Study

The objectives of the study were to identify areas that are more susceptible to landslides; to identify the type of landslides that can occur in the area; and to map the associated slope classes in areas around Khalavha Village. The specific objectives of the paper are to identify the areas which are susceptible to landslides; to identify types of landslides that occur in the study area; and to map slope classes most prone to landslides.

Basic Design of the Study

The basic design of the study and data collection methods are summarized in Figure 2. Some studies have used radar techniques (e.g. DInSAR, PSInSAR) for landslide hazard assessment (Barla *et al.*, 2010; Ermini *et al.*, 2005). Geographical Information System is widely used in

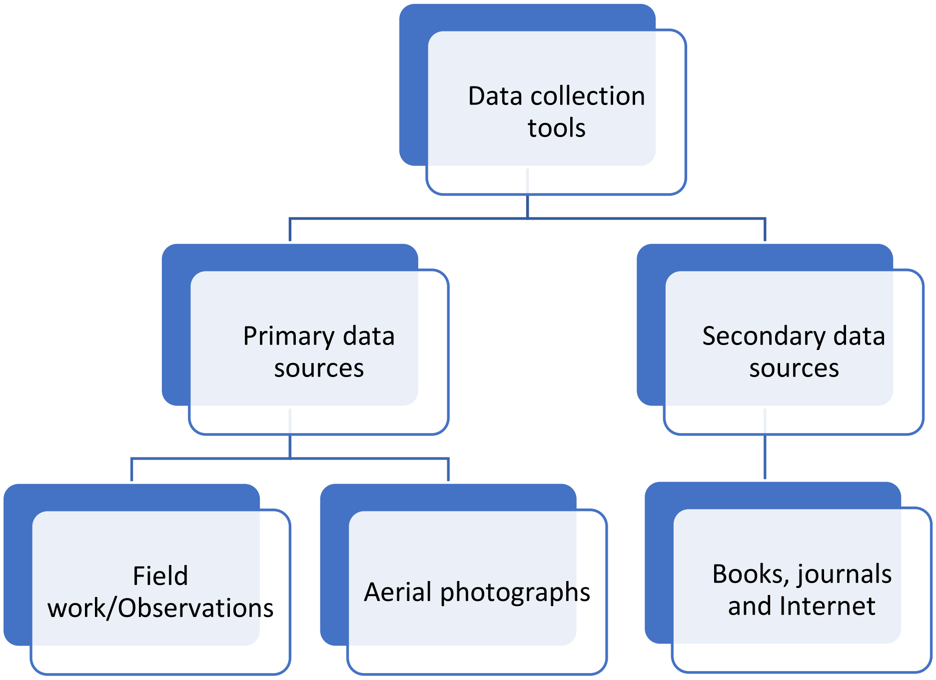


Figure 2: Data collection method to identify type of landslides in the study area.

generation of landslides zoning (LSZ) maps. Several GIS based methods for LSZ that have been developed include for instance, artificial neutral network (ANN), Decision Tree model, Weighted Overlay, analytical hierarchy process (AHP), import vector machine (IVM) (Chang and Liu 2004; Ma *et al.*, 2013). In recent years, radar remotes sensing has added a new dimension to landslide studies. Synthetic aperture radar (SAR) data are increasingly being used either by themselves or in combination with data from other remote sensing sensors.

In South Africa, landslide maps depict potential areas for landslide occurrence, susceptibility, vulnerability, and risk (NRC, 2003). The list also includes inventory maps – which delineate landslide locations from single or multiple triggering events (Wieczorek, 1984). Inventory maps serve as important tools for planners and civil defence forces.

Mapping areas Prone to Landslides

Mapping landslides using remote sensing requires the extraction of relevant spatial information related to landslide occurrences. Remotely Sensed data coupled with Geographical Information System have proved to be effective tools for generating and processing spatial information, and facilitates effective landslide detection, mapping, monitoring and hazard analysis (Tofani *et al.*, 2013). A review of few studies on landslide hazard assessment using RS data shows that aerial photographs (Yeon *et al.*, 2010) are widely used in landslide detection and mapping.

To map areas most prone to landslides, stereoscopic analysis of aerial photographs coupled with field visits was undertaken. Areas prone to landslides were mapped onto an acetate sheet and the interpretation transferred onto a topographic map and digitized in ArcGIS. Digital Elevation Model (DEM) for the area were generated in ArcGIS to determine slope classes and map the geomorphic units. The field visits were done to field check the photographic interpretation, in relation to the features found on the ground and to assess the accuracy of the interpretation and correct any misinterpretations. However, aerial photographs do not have the temporal resolution and are not used in continuous landslide monitoring studies. The use of Digital Elevation Models is also of great importance in mapping of landslide. Several thematic data layers such as slope angle, slope aspect and curvature can be extracted from high resolution DEMs. Landslide hazard zonation studies use high resolution DEMs to generate spatial information data layers related to landslide hazards (Saraf *et al.*, 2009).

Mapping Slope Classes

Slope classes were stereoscopically mapped on the aerial photographs and identified on the DEM; while actual slopes amount and aspect were measured in the field using a staff gauge and a theodolite. The slopes were then grouped into classes based on their percentages as presented in Table 2 and Table 3.

Identification of Landslides Types

The identification of types of landslides that occur around Khalavha Village in Makhado Municipality, required field data observations and interpretation and analysis of remotely sensed data. Field observations were done to assess the triggering factors in the area and to identify the types of landslides that can occur in the area by comparing different triggering factors. Other secondary data were obtained from books, journals and some documents.

Results and Discussion

The main factors responsible for occurrence of landslides in Khalavha Village are steep slope gradients, thick *in situ* soils, human activities, and gullies formation. The type of landslide that occurs mostly in the area is debris flow. In this study, even though geological and geotechnical factors that trigger landslides such as earthquakes and tremors were not studied, future studies should include these factors because South Africa has recently experienced major earthquakes that have shaken most parts of Limpopo Province.

Slope Form

Slopes in the study area can generally be qualitatively described as being either convex, concave or straight in form. Figure 3 shows the view of hill slope in Khalavha Village with houses on critically steep slopes. The slope form shown in Figure 3 is mainly concave in nature, being progressively steeper uphill. Slope curvature influences the susceptibility of a slope to landslides. Figure 3 shows houses built on the foot of the slope and others are at the top of the slope. The negative plan curvature (concave) promotes concentration of flow making the area susceptible to landslides.

Figure 3: View of concave hill slope in Khalavha Village.

Slope Length

The slope length parameter has been considered in many GIS-based applications studies for landslides and soil erosions (Hickey 2000; Gómez and Kavzoglu 2005). Slope length is the distance along a slope that can be subjected to uninterrupted overland flow. Table 2 shows the slope classes and their lengths. Slope lengths are computed on the horizontal and normal angle to the contours of the surface of the slope. Measurements were done in the field and were categorised into very short, short, moderately long, long and very long. Very short slopes have slope lengths which are less than 10m and are straight slopes in form. Most of very short and short slopes are found near the river and within the river valley. Short, moderately long and long slopes are 10-50m and less than 80m. Very long slope forms have lengths is greater than 100m.

Table 2: Slope classes and their length

Slope Class	**Slope Length**
Very short	<10m
Short	10-30m
Moderately long	30-50m
Long	<80m
Very long	>100m

Slope length is an important factor in landslide activity since longer slope lengths increase the potential of erosive agents to transport materials downslope (Gómez and Kavzoglu, 2005). Short slope lengths lead to limited flow velocity; therefore, soil masses do not get enough flow energy to detach and transport materials downslope (Chaplot and Le Bissonnais, 2000).

Relief Aspects

The relationship between relief units, slope steepness and the relative height differences are summarized in Table 3. Slopes are categorised as per the slope classes; and slope steepness is presented as a percentage. The steepest slope which were found around study area were greater than 35%. Landslide occurrences have been observed to be associated with areas of higher relative relief amplitude, typified by rugged, steep, high elevation of mountain ranges (Schulze and Horan, 2007). For example, much of the central region of South Africa is of high elevation, undulating plain with low moderate relief. Steepness is the most important relief characteristics which affects the mechanism and the intensity of the landslides. The greater the steepness and convexity of the slope, the greater the number of the landslides.

Table 3: The relief units, slope steepness and relative height difference

Relief Units	Slope Class	Slope Steepness	Rel.Height Diff
Flat /almost flat topography	A	0-2%	<10m
Gently sloping topography	B	3-6%	10-30m
Moderately steep topography	C	7-12%	30-50m
Steep topography	D	19-25%	50-70m
Very steep topography	E	26-35%	70-100m
Extremely steep topography	F	>35%	>140m

Anthropogenic Activities

There are different activities that are being carried out in Khalavha Village that could trigger landslides are summarised in Table 4. These activities can change slope geometry and accelerates the occurrence of landslides, or can play a significant role in the occurrence of landslides (Cheng *et al.*, 2007).

Table 4: Land use activities, classes and area affected.

Activities	Activity's class				Area affected (%)
	None	Slight	Moderate	Severe	
Cultivation				✓	>75%
Excavation			✓		25-60%
Deforestation				✓	>75%

Anthropogenic activities which can change the slope form undertaken in the Khalavha study area include subsistence cultivation, excavation and deforestation. When these activities are undertaken, they contribute to slope instability which leads to susceptibility to landslides. Subsistence agriculture in the area is greater than 75% (NEMA, 2010). Agricultural activities on hill slopes loosen soil structure, increases porosity, permeability and run-off, enhancing deep weathering and reduces the overall shearing strength of soils (Analgen 1992; Ercanoglu & Gokceoglu 2002; Knapen *et al.*

2006). Most of the subsistence cultivation is undertaken along the river valley, which increases the chances of landslides occurrence.

Due to increasing population pressure in Khalavha Village, for construction purposes buildings/houses are constructed on steep to very steep slopes by digging foundations on loose regolith and overburden (Figure 4). Most of the foundations for the houses do not have retaining walls or any form of protection (Figure 4) thereby increasing the danger of potential landslides. Several studies have found that slope undercutting decreases hill slope stability. In 2007 in the Bulecheke area (in South Africa), excavation for building a house was directly responsible for triggering slope failure and creep phenomena that caused a landslide which killed two young girls in a house that collapsed (NEMA, 2010).

Deforestation in Khalavha Village is evident through the slash and burn technique, where trees and vegetation cover are removed for different purposes; these methods have been adopted by most of the steep hill-slope dwellers (Figure 5). In most of the East African highlands deforestation is one of the main preparatory factors for landslides (Odhiambo and Rivereau, 1982). Stability analysis shows that deforestation decreases the safety factor, which is a measure of the slope stability. In the Khalavha area, deforestation (through slash and burn for subsistence agriculture or harvesting wood fuel) which is very severe is practiced along river valleys and on the steep slopes by most people. Removal of the vegetation cover (Figure 5) decreases slope stability by affecting the hydrology and mechanical properties of soil masses on steep slopes and thereby increases the chances of landslide occurrence.

Figure 4: Digging of foundations on steep slopes with thick soils.

Figure 5: Slash and burn of vegetation.

The Landslide Susceptibility Map

Landslide susceptibility maps simply provide an indication of areas where landslides may occur by ranking the slope stability of an area into categories ranging from stable to unstable (Anon, 2011). Landslide prone areas can be described as the relative likelihood of future land sliding which are solely based on the intrinsic properties of the location or site. The landslide prone areas map highlights areas of possible future landslide occurrence and can be interpreted in relation to the potential devastation of environments or infrastructure present in the different areas.

Slope which has a direct effect on landslide processes, is frequently used as one of the major factors in landslide susceptibility mapping. In the study area, slopes were categorized from the smallest (least prone to landslides) to the highest slopes (the steepest areas; most prone to landslides). The slope classes together with the areas prone to landslides are illustrated in Figure 6. This figure was created using both interpretation of aerial photographs together with Digital Elevation Model (record absolute elevation at a spatial resolution of 90m) data obtained from Shuttle Radar Topography Mission (SRTM) and downloaded in ArcGIS 10.5. Table 5 is the legend for Figure 6 which shows slope classes and the landslide prone areas. The details are described in the following section.

Table 5: Legend for Figure 6 showing the Slope Classes and Landslide Prone Areas

🟩	**Low landslide susceptibility:** Within these areas there is a low potential to adversely influence slope stability. These are often associated with low slopes.
🟨	**Moderate landslide susceptibility:** These are areas for which the combination of factors may have a moderately adverse influence on slope stability.
🟥	**High landslide susceptibility**: These areas have a high potential for slope instability and are predominantly associated with steep slopes and high relief.

The Landslide Susceptibility Map of Khalavha Village (LSM, Figure 6) simple colour scheme is used to characterize areas into three main slope–stability zones. The colour renditions green, yellow and red represent areas that are potentially stable (green), areas that are moderately stable (yellow) and least stable areas (red). The LSM map (Figure 6) was compiled based on the slopes/terrain units recommended by Brabb *et al.*, (1972); in which assessment of a regions' landslide susceptibility employs slope angle as one of the major factors.

The low landslide susceptibility areas (Green) generally represent flat terrain surfaces, with low slopes ranging between 0° - 20°. These areas are suitable for all types of development; even though sever Earthquakes can also cause serious damage even in flat areas as was witnessed in the devastating Indonesian Oct 2018 Earthquake event, when the soils become liquefied and flows. Therefore, development in these areas should be guided by normal planning and building regulations because there is generally no (little) threat that can emanate from landslides.

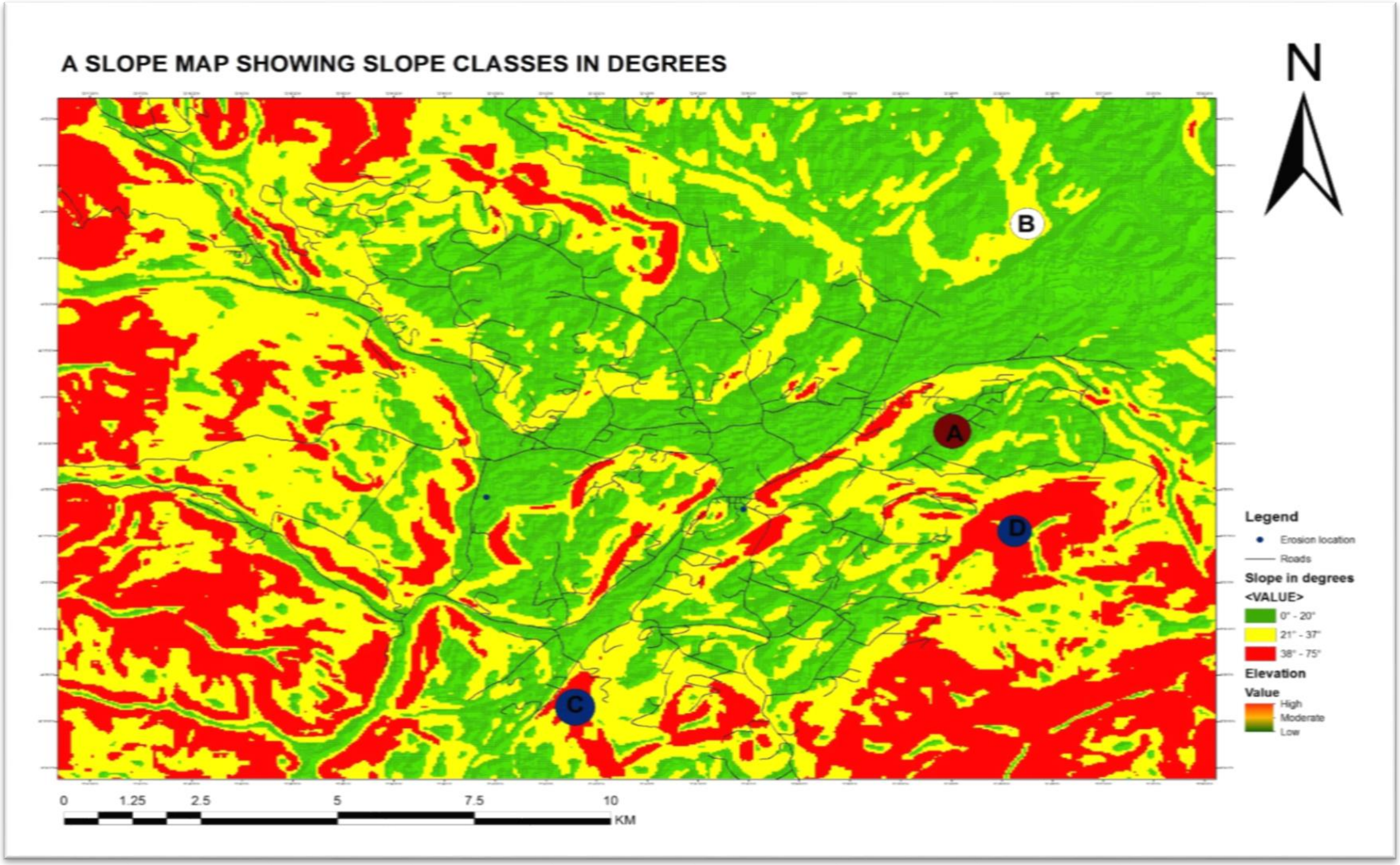
In the low landslide susceptibility areas (Green) the land surface is generally degraded through sheet erosion (in Figure 6 at Location A). Sheet erosion is mostly prevalent along roads and on some farms. It exposes the stony soil where there is no vegetation cover to protect the soil. Early signs used to identify sheet erosion include bare areas, water paddling as soon as rain falls, visible grass roots, exposed tree roots, and exposed subsoil or stony soils. Vegetation cover is vital to prevent sheet erosion because it protects the soil, impedes water flow and encourages water infiltration into the soil (Selby, 1993).

The Moderate landslide susceptibility area (Yellow regions in Figure 6) has slopes ranging between 21°-37°. These slopes are moderately steep to steep. The yellow color rendition represents areas where landslide susceptibity is moderate; landslides are more likely to occur and threats from landslides are moderately higher. These areas are generally suitable for residential housing if other site suitability conditions are met and adequate preparations are made based on detailed geotechnical investigations and advice. The scale and nature of proposed development should be taken into consideration. The cost of investigations and remedial and/or preventive measures are likely to be high.

In this moderately steep to steep areas, rill erosion (Fig. 7), that is the dominant erosional process, is characterized by shallow drainage erosional channels that are less than 30cm deep. Rill erosion is intermediate stage between sheet erosion and gully erosion (Singh, 2010). Rill erosion around Khalavha Village is found mostly areas near river valleys (Location B in Fig. 6).

High landslide susceptibility areas (Red in Figure 6) have steep slopes more than 38°. These areas are generally too steep for development, have high cost factors with respect

Figure 6: Slope classes and areas prone to landslides around Khalavha Village, Limpopo Province.



to low and or middle income residential housing. The high landslide susceptibility areas have the highest potential for instability and have been deemed to be too steep for formal low cost housing development in the area around Khalavha Village. Generally, the steeper the slope the less stable it is, hence the potential for landslides increases with higher slope angles.

Fig. 7: Rill erosion at Location B in Fig. 6.

Fig.8: Gully erosion at Location C and D in Figure 6.

Erosional gullies (channels deeper than 30cm) are prevalent in the high landslide susceptibility areas around Khalavha Village, especially in places near the rivers, on farms, and along the roads (Figure 8 at location C and D in Figure 6). Some studies show that landslide occurrences may be caused by severe gully erosion.

The western and southeastern sections of the Landslide Susceptibility Map (LSM) are the high landslide susceptibility areas that have slopes which are steep, very steep and extremely steep. The area is generally in high relief mountain regions that have deeply incised river valleys (Winser, 2013). The area is prone to landslide occurrence, and human live and property in these areas are in great danger of being affected by landslides. Dwellings in this class should be evacuated to safer areas. In general, these areas are unsuitable for site development, and the costs for standard geotechnical investigations and remedial measures or preventive work for slope stabilization may be very high.

Conclusions

Whereas it is not easy to predict neither landslide occurrence nor the type of landslide that can occur in an area, the type of landslides that are prevalent in the area occur in the form of a mudflow. The possibilities of increasing mudflows occurrence is enhanced by excavation of the steep slopes for construction of housing. These excavations are undertaken in thick soils that occur in areas with steep to very steep slope gradients. In these areas deforestation and removal of vegetation on slopes is prevalent as is cultivation on steep slopes. These anthropogenic factors enhance the possibility of devastating landslides especially during the rainfall season when heavy torrential rains are experienced.

It is therefore concluded that human activities, rainfall, deforestation, gullies, land use, slope steepness and increased agricultural activities are factors that can easily trigger the occurrence of landslide (mudflow) at Khalavha Village. An increase in population enhances depletion of environmental resources and increases the rate of deforestation, a factor that increases landslide activity in mountainous regions.

Recommendations

The study recommends that deforestation should have severe penalties and extensive forestation programs should be implemented. Excavations for development of residential housing should have earth retaining walls to protect the properties from rock fall or soil creep**.** The study recommends that sustainable communication through educating the residents of Khalavha Village is most effective way to reduce the loses through landslides occurrence in the area, especially for those who live steep to very steep slope areas. Construction of homes in the High Landslide Susceptibility areas (Red in Figure 6) due to the high rising population should be discouraged.

Lastly, it is important to indicate that during the last 15 years, South Africa has experienced several earthquakes (>4.0 ML) that have resulted in shaking most parts of Limpopo Province. Scientific publications have warned of the likelihood of the occurrence of very severe earthquakes in the country. Significant contribution to devastating earthquakes come from mining activities and water ingress in previously mined areas. These could adversely affect the lives of several million people in country. The earthquake that occurred on 4th April 2017 with its epicenter in Botswana, should lead to revision of the seismic zoning map of South Africa and recommend deletion of the non-seismic zone from the map in areas previously thought to be safe from impacts associated with earthquakes. This recent earthquake event that shook parts of Limpopo Province, suggests that as understanding of the seismic hazards of these regions increases, more areas assigned as of low hazards may be re-designated to higher levels of seismic hazards. A seismic risk hazard map can be produced to mitigate against the risks that may be associated with earthquakes.

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