LANDSLIDE GEOHAZARDS IN SOUTH AFRICA:

Landslide susceptibility mapping, socio-economic impacts, mitigation and remediation measures

By

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1. INTRODUCTION

A landslide is defined by Cruden (1991) as "the movement of a mass of rock, debris, or earth down a slope." Most frequently used landslide classification systems are based on the type of movement and material (Varnes, 1978 and Cruden and Varnes, 1996). There are five types of landslides; falls, topples, flows, slides (translational and rotational) and lateral spreads. Short descriptions of these landslide types, following Varnes (1978), Cruden and Varnes (1996) and Highland (2004), are provided in Fig. 1.

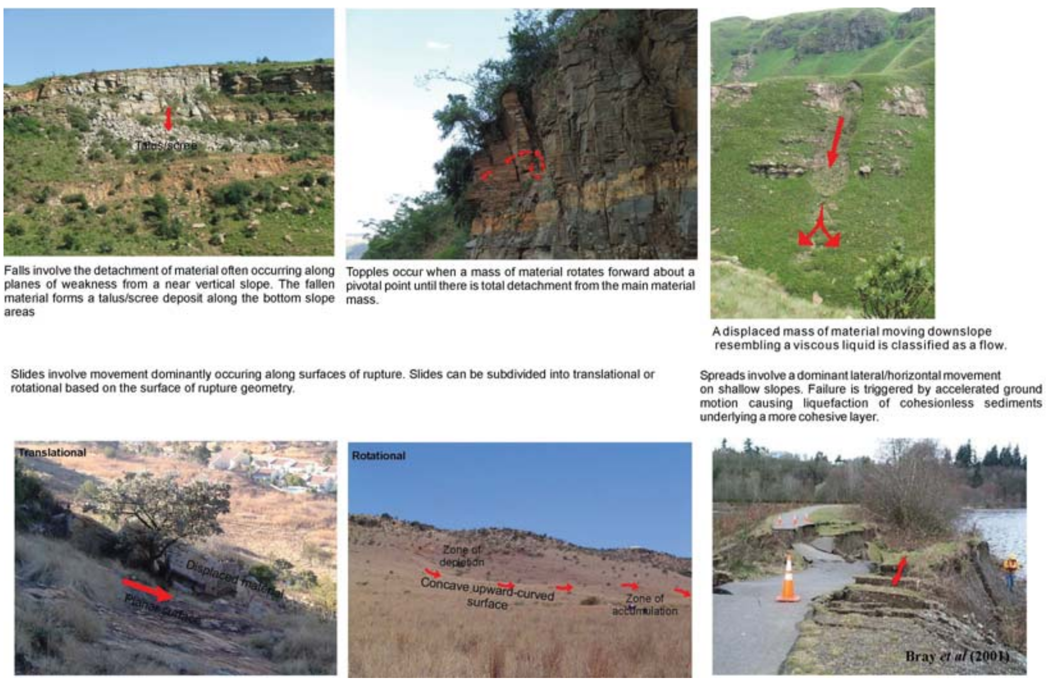


Figure 1: Graphic illustrating various types of landslides.

In 1989 the estimated annual costs of landslide associated expenses in southern Africa, were estimated at approximately US$ 20 million (Paige-Green, 1989). Based on an annual standard inflation rate of 10%, the current suggested amount means that annual landslide associated expenses would cost southern Africa ~US$ 163 million. Many countries around the world suffer significant economical impacts associated with landslide activity. Landslide costs in South Africa are often associated with severe, high intensity rainfall events that result in damage to infrastructure. The steep terrain, considerable topographic variation, high relief, diverse geology, humid climate and seismicity make some parts of South Africa (Fig. 2) susceptible to landslide activity.

A recent example of landslide socio-economic impact in South Africa was the damage to the Kaaimans Pass road in 2006. Slope failure resulted in the complete closure of the N2 highway. It initially impacted on all traffic for two days and a further period of two weeks thereafter with respect to heavy vehicles. Local businesses had to bear the cost of a 900km return detour instead of the usual 150km round trip, between George and Knysna. Long haul carriers between Cape Town and Port Elizabeth/East London/Durban were also forced to make lengthy detours via less suitable tarred provincial roads. This incident highlights the necessity for proactive landslide studies and the implementation of expanded mitigation strategies and active monitoring systems. Apart from having serious economic impacts, landslides are often life-threatening. In South Africa, mass movement fatalities occurred during the Merriespruit tailings dam failure in 1994 (Wagener, 1994), the Stanger debris flow of 1987 and recurring rockfalls from the mountain slopes above Chapman's Peak Drive along the Atlantic coastline, have killed road users. It is clear that geohazards, including landslides, should be a primary consideration in all spatial development planning frameworks.

1.1 Landslide inventory and mapping

There are four types of maps that are produced by landslide experts that could aid decision making. These maps are described below according to Anon, 2011 (USGS, website)

i) Landslide inventory map

"This type of map shows the *locations and outlines of landslides.* A landslide inventory is a data set that may present a single event, a regional event, or multiple events. Small-scale maps may show only landslide locations whereas large-scale maps may distinguish landslide sources from deposits and classify different kinds of landslides and show other pertinent data."

ii) Landslide hazard map

"A landslide hazard map indicates the *possibility of landslides occurring* throughout a given area. A simple hazard map may use the locations of old landslides to indicate potential instability in the surrounding area. More complex, quantitative approaches produce maps incorporating probabilities based on variables such as rainfall thresholds, slope angle, soil type, and levels of earthquake shaking. An ideal landslide hazard map shows not only the chances that a landslide may form at a particular place, but also the chance that it may travel down-slope a given distance."

iii) Landslide susceptibility map

"These maps rank slope stability of an area into categories that range from stable to unstable. Susceptibility maps show *where landslides may form*. Many susceptibility maps use a color scheme that relates warm colors (red, orange, and yellow) to unstable and marginally unstable areas and cool colors (blue and green) to stable areas."

iv) Landslide risk map

"This type of map shows the *expected annual cost of landslide damage* throughout an area. Risk maps combine the probability information from a landslide hazard map with an analysis of all possible consequences (property damage, casualties, and loss of service)."

The Council for Geoscience (CGS) has been involved in landslide research which highlighted this geohazard as a significant, widespread geomorphological threat in some parts of South Africa (Singh et al., 2010). Landslide research within the CGS also produced landslide susceptibility maps for KwaZulu Natal and Limpopo provinces as well as parts of the Eastern Cape and Western Cape. An early landslide susceptibility map of Southern Africa was compiled by Paige–Green (1985), based on factors such as geomorphology, water, and geology. A revised map of southern Africa by Paige–Green and Croukamp (2004) was developed in the Geographic Information System environment. The revised map used a combination of geological information, digital terrain information, the water surplus provinces and seismic information.

The primary aim of the landslide element of the Department of Science Technology (DST) funded Earth Observation and Geohazard Assessment project will be to produce an improved landslide susceptibility map of South Africa.

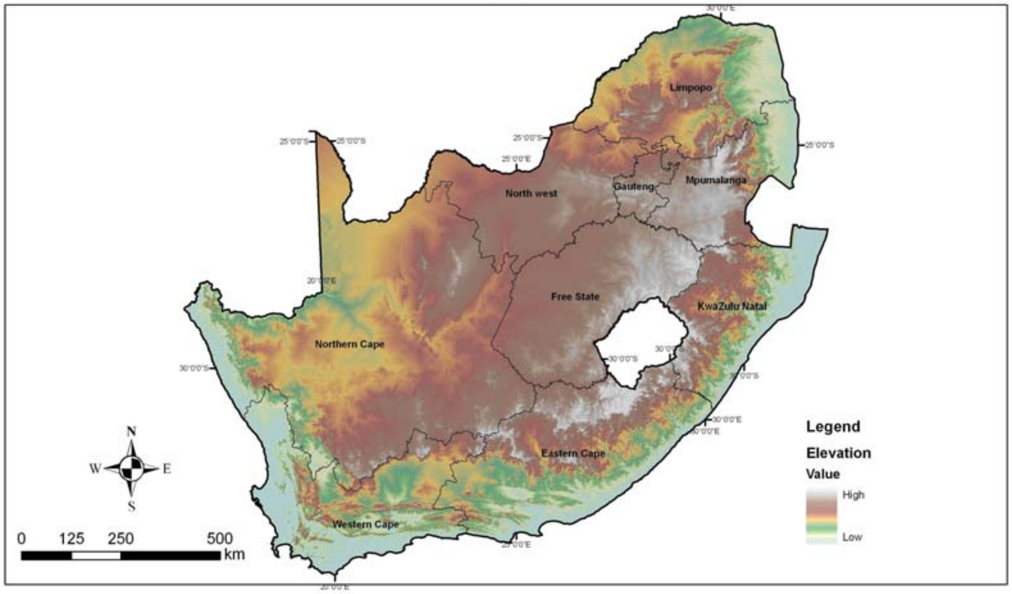


Figure 2 Locality map of South Africa showing the provincial boundaries of all nine provinces.

2. LANDSLIDE OCCURRENCES IN SOUTH AFRICA

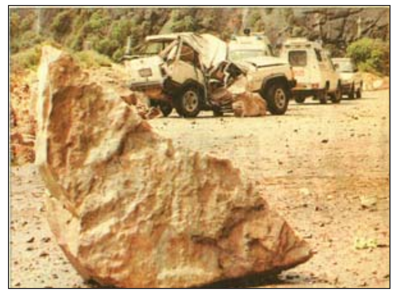
It must be emphasized that only a small selection of SA landslides are illustrated and not all nine provinces are represented due to data deficiencies. A few examples of landslides in the Western Cape, Limpopo and KwaZulu-Natal provinces are described in Fig. 3.

Province	Description
Western Cape	 Outeniqua Pass: N12 highway, January 2011 Large rock slides have caused road closures.  Outeniqua Pass: N12 highway, January 2011 Ongoing rockfalls also occur.

Du Toits Kloof Pass, old N1 route.
Recurring rockfalls & debris flows disrupted traffic

Du Toits Kloof Pass, N1 highway north of tunnel
The June 1991 Molenaars Peak debris flow.


Chapmans Peak Drive, June 1994
Wet debris fall resulted in drivers leg paralysis
[Rapport 20/09/1998]


Chapmans Peak Drive, November 1997
Rockfall caused one death
[Sunday Times 18/09/1998]


Kaaimans Pass: August 2006: Failure #1 site
Highway, house at left and railway below affected.
[M Mohlabane, BKS]


Kaaimans Pass: Failure #2 site
Dip slope translational type failure.
[M Mohlabane, BKS]

Province	Description	
Limpopo	 Aerial view of Lake Fundudzi: A palaeo feature formed by a rock avalanche 20000 years ago. (van der Waal, 1987) [G Chiliza 2008: both images]	 The towering quartzite cliff failure scarp above the dammed Mutale River, Soutpansberg mountains. Past seismicity, toe under cutting and rock shear failure occurred.

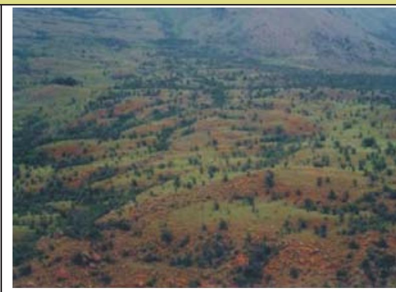
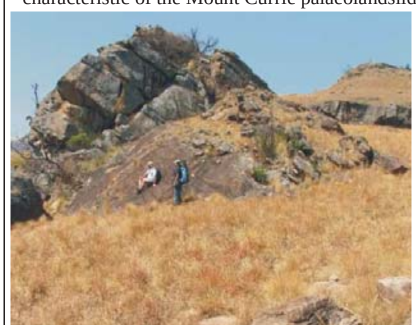
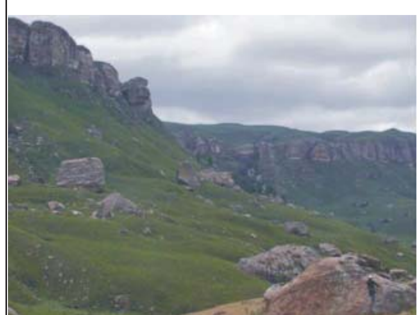
Province	Description	
KwaZulu-Natal	 Aerial view of the Mount Currie Holocene landslide	 Typical widespread hummocky topography characteristic of the Mount Currie palaeolandslide
	 Aerial view of the Meander Stream rotational palaeolandslide in the Giants Castle Nature reserve	 Large rotated sandstone/mudstone intact blocks dipping into the failed slope at steep angles form part of the Meander Stream palaeolandslide debris
	 Ongoing rock failures in the Highmoor Nature reserve.	 Widespread rockfall scree characterise many slopes below the distinct Clarens Formation Cliffs in the uKhahlamba Drakensberg mountains

Figure 3 Examples of landslides in Western Cape, Limpopo and KwaZula-Natal.

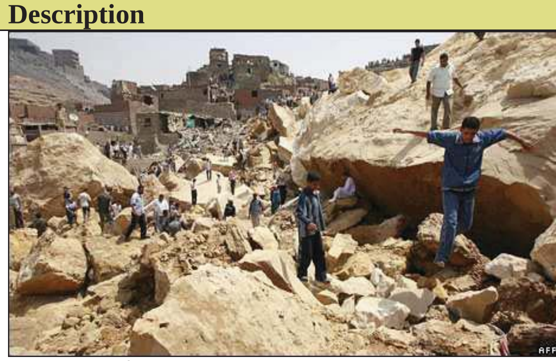
3. EXAMPLES OF LANDSLIDES ELSEWHERE IN THE WORLD

A short 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:

(i) a low overall seismic and tectonic hazard regime compared to locations such as California, Peru, Japan, China, Turkey and Pakistan where this geohazard is a major triggering factor of mass movements.

(ii) a low incidence of tropical cyclones such as those annually affecting areas such as Jamaica, Haiti, Indonesia, Japan and the USA states of Alabama and Carolina where associated intense rainfall have trigged numerous debris flows and shallow landslides.

Examples from Egypt, China and Brazil are described briefly in Fig. 4.

Country	Description	
Egypt	 Immediately after the 6 September 2008 Duwaiqa event. Confirmed deaths stood at 107 with more bodies still buried under massive sandstone blocks. [Source: web news site]  18 September 2008: Quick Bird view of affected houses, at the foot of the collapsed cliffs (centre) [Source: web: Dave Petley (ICL), pers blog	Slow rock creep combined with unfavourable discontinuity orientations, plus possible cliff undercutting by shanty town dwellers, resulted in an unexpected and dramatic rock avalanche, in a slum district of Cairo in September 2008. Collapse of just 100m of the Muqattam plateau edge resulted in 6000m^2 of damage, below.

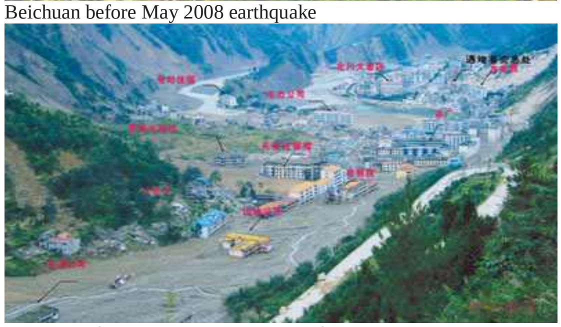
Country	Description	
China	 Beichuan before May 2008 earthquake  Beichuan after September 2008 debris flows.	The MMI 5.1 Wenchaun earthquake of May 2008 triggered numerous landslides and rockfalls in Beichaun City. Subsequent heavy rains, in September 2008, further mobilized these loosened materials, resulting in some 72 debris flows and 42 deaths in Beichaun County (Tang C et al, 2009). Some inundated the older parts of Beichuan city, that had previously been evacuated after the May 2008 earthquake triggered events.
Country	**Description**	
Brazil	 Teresopolis: January 2011: Extensive mud sliding & debris flows [web news site]  Teresopolis: January 2011: Mass movement damage.[web news site]	A combination of deeply weathered soils and frequent incidences of high rainfall, often lead to devastating landslides in Brazil. On 12 January 2011 debris flows and mudslides caused 200 tragic deaths and severe infrastructure damage, at Teresopolis village.

Figure 4 Description and examples of international landslides

4. LANDSLIDE INVENTORY AND SUSCEPTIBILITY METHODOLOGY

The initial phase of study involved the compilation of all the CGS landslide inventory data and literature. The landslide susceptibility modelling methodology has followed the hypothesis which suggests that slope-failures in the future will be more likely to occur under those conditions which led to slope instability and failure in the past (Ermini et al, 2005).

During the second phase of this desktop study, different types of landslide susceptibility modelling techniques were used, namely;

(i) the bivariate statistical landslide susceptibility modelling method (Soeters and van Westen, 1996) aided by the Analytical Hierarchy Process (AHP) (Saaty 1980).

(ii) the weights of evidence/logistic regression method was used to produce a comparative map of national landslide susceptibility.

The final phase consisted of a quality control or accuracy assessment where landslide test points, independent of those landslides incorporated in the initial landslide susceptibility modelling exercise, were compared with the landslide susceptibility maps produced.

5. LANDSLIDE MECHANISMS - CONDITIONS LEADING TO THE HAZARD

Landslide research in South Africa has shown that slope failure is often associated with steep slopes, prominent topographic variance, high relief, diverse geology, humid climate, considerable seismic activity and anthropogenic influences. These factors have a highly varied influence on slope instability, some of which have a far greater impact than others. Certain landslides causes are inherent in the composition or structure of the bedrock or soil; whereas anthropogenic activities are imposed. Landslide causal factors such as gradient of undisturbed slopes are relatively constant as opposed to variable influences such as groundwater. Seismic vibration is an example of a transient factor. To identify areas of potential slope instability, it is important to evaluate the various critical landslide causal factors affecting landslide activity in the study region. The following landslide influencing parameters, with the exception of human-initiated effects, were selected for the national-scale landslide susceptibility analyses.

5.1 Slope Angle

The major variable that defines the causative force is the angle of the potential sliding surfaces. At local scales it affects the concentration of moisture and the level of pore pressure and is often useful to resolve detailed patterns of instability. At larger scales it controls regional hydraulic continuity and is considered as an important factor for GIS-based landslide susceptibility mapping by many authors. Slope inclination is often grouped into ranges of degrees (Fig. 6) or percentage and special maps showing these ranges may be constructed.

Generally, the steeper the angle, the greater the likelihood of a landslide. According to Partridge et al, (1993) slope angles of >12° are deemed to be too steep for formal housing development, in KwaZulu-Natal and Western Cape however, this angle has been increased to >18°. It must be emphasized, however, that under certain conditions the potential of instability may exist in areas with shallow slope angles. For example, sandy soils associated with high ground water level conditions may liquefy during an earthquake, causing a landslide on a slope as gentle as 5–10%. Conversely, the steepest slopes may not always be the most hazardous since high gradient slopes are less likely to develop a thick cover of superficial material conducive to lateral spreading.

5.2 Relative relief

Relative relief (Fig. 6), as explained by Schulze and Horan (2007), is an index of topographic variance or hilliness of an area. Landslide occurrences have been observed to be associated with areas of higher relative relief, typified by the rugged, steep, high elevation mountain ranges in South Africa.

Much of the central region of South Africa is a high elevation, undulating plain with low to moderate relief. It is separated from the surrounding coastal hinterland areas by the Great Escarpment, which ranges in height from about 1 500 m in the Roggeveld region of the Northern/Western Cape in the southwest to nearly 3 500 m in the Ukhahlamba-Drakensberg region of KwaZulu-Natal. The elevation of the high elevation interior plains decreases gradually from east to west (Fig.5, after Moon and Dardis, 1988).

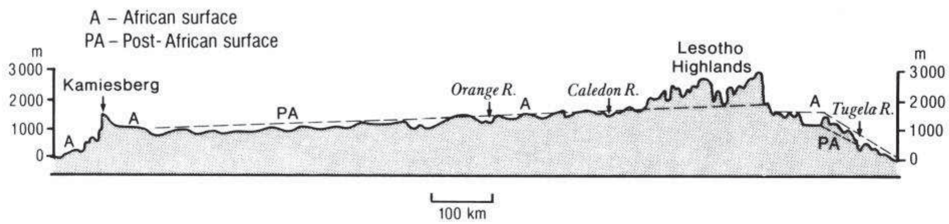


Figure 5 Simplified topographic profile across South Africa showing the steep eastern slope, the Lesotho highlands and the gradual descent towards the west coast (after Moon and Dardis, 1988).

The central part of the interior plateau comprises the “Highveld” which covers an elevation range of 1,200 to 1,800 m. South of the Orange River lies the Great Karoo region.

The Great Escarpment can be traced southward from the far northeast of South Africa where it is generally known as the Transvaal Drakensberg. It is in the KwaZulu-Natal province that some of the country’s highest elevations can be found, Njesuthi (3,408 m) and Mont aux Sources (3,299 m), where the escarpment forms the eastern boundary of the dissected Lesotho highlands. Towards the southwest the escarpment extends across the Eastern Cape at lesser elevations of 1,500 to 2,400 m in the Stormberg mountains, becoming the Nuweveld Range and the Roggeveld Mountains. At its western extreme, in the vicinity of Mount Bokkeveld and Mount Kamies (1,700 m), the escarpment is not well defined. The Cape Fold Mountains along the Southern and Western Cape coastal hinterland is an area of high relief and steep slopes where landslides are a common occurrence. Slope failure is a common phenomenon in the Tsitsikama, Outeniqua, Groot-Swart, Langeberg, Cederberg, Drakenstein, and Hottentots Holland mountains, as well as along Table Mountain and its associated features at Cape Town.

5.3 Rainfall

Water is recognized to be a factor almost as important as gravity in slope instability. Therefore, identification of the source, movement, volume of water, and water pressure is very important. The type and severity of slope failures vary from region to region depending on the local climatic patterns of temperature and precipitation, (known as the Weinert N-value) as well as the soils and weathering products characteristic of the variety of rock types in each climatic region. The mean annual precipitation map by Schulze and Lynch (2007) was incorporated in the modelling of landslide susceptibility of South Africa (Fig. 6).

The rainfall information presented below is described according to Anon, 2011 (Enviro-Info 2001 website and Holiday Weather - South Africa website). The climate of South Africa is generally semi-arid with highly variable precipitation and seasonal rainfall deficits. More than one-fifth of the country is arid and receives less than 200 mm of precipitation annually, while about 35% of southern Africa receives less than 300 mm per annum. This is due to the presence of subtropical high pressure cells which inhibit rainfall generation because of the predominantly subsiding air. Only about 6% of the country averages more than 1,000 mm rainfall per year, such as along the KwaZulu-Natal coast. The amount of precipitation declines gradually from east to west. Between the escarpment and the ocean in both the southern and the eastern coastal margins, the rainfall patterns are complex due to irregular terrain morphology. The Drakensberg Mountains run almost parallel to the coast along the entire eastern part of the country, causing the irregular rainfall patterns in that part of South Africa. In the interior, Kimberley receives approximately 400 mm precipitation whereas Alexander Bay on the west coast receives less than 50 mm.

According to Thomas and van Schalkwyk (1991) prolonged precipitation events associated with high intensity rainfall often trigger landslides such as the heavy rainfalls of September 1987 and February 1988 occurring in KwaZulu-Natal. In February 2000, eye-witness accounts and field investigation showed that many slope failures occurred after intense and unusual heavy rains within a short timespan. The rains resulted from three low pressure systems, namely, the Eline and Gloria tropical cyclones, and additionally, a somewhat lesser nucleus of low pressure. Countless roads, bridges and other public and private properties were damaged, while 101 people lost their lives (Limpopo Provincial Disaster Management Unit, 2000)

5.4 Geology

It is widely recognized that geology greatly influences the occurrence of landslides because different rock types exhibit varying resistance to weathering and erosion processes. This is primarily due to geological structures such as joints, faults and folds, associated with the particular rock formation. The attitude or dip and strike of the stratigraphic sequence, abrupt changes in lithological character and bedding planes have a strong influence on the strength characteristics of a rockmass. Mineralogical influences are of fairly minor significance in unweathered material, where it is the discontinuity strength and not the material strength that determines stability. As weathering proceeds, however, the material strength will decrease and may become lower than the discontinuity strength as newly formed clay minerals develop from the weathered original minerals.

The lithological map (Fig 6) used in the landslide susceptibility modelling of South Africa was derived from the CGS 1:1 000 000-scale geological spatial data. Lithological successions, or at a larger scale the stratigraphic sequence, can influence slope stability particularly if beds are slightly dipping. In areas where the topographic surfaces are steeper than bedding planes, over-dip slopes are formed. Under-dip slopes are common in areas where bedding planes are steeper than the topographic surfaces. In addition, zones for dip-slopes where the slopes and rock beds are inclined parallel to each other are also found. High possibility of failure exists in over-dip slopes where bedding planes daylight on the topographic surface.

Interbedded shales and sandstones are commonly more susceptible to failure than either type alone, mainly because the coarser units may transmit water more readily to the weaker, and less permeable bed interfaces, with a concomitant rise in pore water pressure and loss of shear strength.

These lithological and rock mass variations are important in determining the shear strength, permeability, susceptibility to chemical and physical weathering, and other characteristics of soil and rock materials, which in turn affect slope stability. For example, soft rocks such as mudstones, tillites, phyllites and slates are generally more susceptible to landslides than hard and compact rocks like granite and limestone. In addition, soils derived from weathered schists, shales or mafic rocks will contain high percentages of clay. The strength characteristics of fine textured soils are thus very different from the coarser-grained soils such as those derived from granitic bedrock.

In South Africa, landslide mapping has, however shown that rockfalls are a common occurrence, often associated with resistant regionally metamorphosed and jointed sedimentary strata. Disengagement of blocks from the near–vertical rock faces depends on local discontinuity orientations and at certain times ice wedging Areas of tectonically tilted strata such as the Cape Fold Belt have resultant steep dips and are characterized by such inherent instability. Patches of highly to completely weathered Cape Supergroup quartzitic sandstone at high altitudes are also commonly mobilized in landslide events. Differential weathering of less competent lithologies usually results in slope undercutting and instability. This occurs in the Western Cape where quartzites overlie deeply weathered Cape Granites.

5.5 Seismicity

In seismically active parts of the world, some of the most disastrous of all historic landslides have been triggered by seismic shock events. Particularly susceptible materials are those with a loose or open structure such as loess, volcanic ash on steep slopes, saturated sands of low density, fine-grained 'sensitive' deposits of clay or rock flour, and cliffs of fractured rock or ice.

Earthquakes with magnitudes 4.0 or greater are often strong enough to cause landslides, however, the possibility of an occasional small seismic event Ml < 4.0 triggering landslides should not be disregarded (Keefer, 1984). Southern Africa has intra-plate continental margins and is regarded as being relatively stable from a geological and tectonic perspective. Generally the seismicity of Southern Africa is very moderate and of shallow character relative to world standards (Brandt et al, 2005). According to the Earthquake catalogues of the Council for Geoscience, there are two types of seismic events that occur in southern Africa, namely natural earthquakes and mine tremors in the East, Central, West and Far West Rand and Free State gold mining areas as well as in the vicinity of the Rustenburg platinum mines and the Mpumalanga coal mines. Intraplate seismicity characterizes South Africa, and occasional natural seismic activity occurs sporadically within all provinces. The correlation of seismic events to mass movement events is very difficult to quantify in such a seismically quiet environment. However, certain zones of more concentrated seismicity have been recognized and are associated with higher ground acceleration (Fig. 6). For example reports of rockfalls and other mass movement events linked to mining activities, were found in fact to have occurred at the time of the 1969 Ceres MMl 6 earthquake

In this study the landslide susceptibility assessments of South Africa used Fernandez and du Plessis (1992) seismic map data. This seismic hazard map (Fig 6) shows peak horizontal ground acceleration (PGA) levels that have a 10 percent probability of being exceeded, at least once, in a period of 50 years.

5.6 Terrain morphology

Terrain morphology, through control of flow sources, flow direction and soil moisture concentration, is an important factor that limits the density and spatial extent of landslides. If a region is rugged with many steep hills, it will be far more susceptible to instability than a gently rolling or flat region, owing to the geological and soil cover influences described above as well as the necessity for deeper cuttings and higher embankments associated with development.

According to Schulze and Kruger (2007), the terrain morphology of South Africa, Lesotho and Swaziland can broadly be subdivided into plains, lowlands, open and closed hills, low and high mountains and table lands (Fig. 6). High elevation plains with low to moderate relief dominates the topography and characterizes large parts of the country's interior. The Great Escarpment, comprising high mountains, defines a dramatic terrain morphological contrast with the lower elevation, dissected river basins of the surrounding areas.

Ridges, mountains, and deeply incised valleys are common, mainly left by the erosion of ancient landforms. A number of erosion cycles resulted in dissected, youthful topography with steep hills and deep valleys. This youthful topography is particularly prone to instability, owing to inadequate natural stabilization of the slopes at optimum angles. Any injudicious removal of part of the natural slope will usually result in instability of the remainder of the slope.

5.7 Dolerite contact zones

Many of the larger slope failures in KZN and the northern part of the Eastern Cape have a definite association with dolerite intrusions (van Schalkwyk and Thomas,

1991) due to the differential weathering between the dolerite and sedimentary country rocks which create areas of steepened topography and/or high relief. At a local scale, strata disruption of the country rock may be attributed to dolerite sill and dyke intrusions. In some instances bedding planes can even dip at angles that are concordant with steep slope gradients, making them highly susceptible to slope failure.

The spheroidal weathering profile in dolerite forms hard corestones surrounded by soft, porous clayey saprolite that stores shallow groundwater. Groundwater saturation may increase pore pressure within the weathering profile and reduce rockmass strength. Contact zones between dolerite and country rocks (Fig. 6) as well as the dense vertical joint planes within the dolerites generally act as zones of groundwater migration. Seasonal groundwater saturation or infiltration following extreme rainfall events may increase pore pressures within the weathering profile associated with these zones and reduce regolith or rockmass strength.

5.8 Lineaments

The study of lineaments may help reveal structural fabrics that could assist in understanding the cause of landslides in a region. Lineaments include tectonic structures, juxtaposed rock units, intrusive dykes and geomorphologic signatures such as topographic breaks. Detailed lineament, fault and dykes studies documented three major trends in the basement and cover rocks of KZN, namely N–S and WNW and ENE (Von Veh, 1995) whereas in the Table Mountain Group, the results of directional analysis showed that there are principally three striking directions: NE-SW, NW-SE, and near E-W (Fig 6).

These linear structures, commonly tracing faults, closely-spaced joints or dolerite dykes, are likely to stimulate mass movement for several reasons. Most importantly, these linear features form discontinuities of low strength that interact with gravitational forces wherever local relief and dissection permit. Lineaments tend to concentrate infiltration of rain- or groundwater, giving rise to increased pore pressure. Increased moisture percolation and associated reduced friction along these zones of weakness causes material above the affected plane to slide. Fracture traces are zones of preferential weathering, especially where the fracture has led to cataclasis.

5.9 Human-initiated effects

In addition to natural phenomena, human activities may increase the natural tendency for a landslide to occur. Landslides resulting from development activities are usually the consequence of increased soil moisture content or changes in slope angle or form. Losses of grassland or forest vegetation cover by overgrazing, fire, or clear-cut logging not only alters the hydrologic conditions of a slope, but is widely believed to promote rapid run-off and erosion, thus increasing the possibility of slides and debris flows. Removal of lateral support by man's activities is an important cause of slope failures in cuts for roads or housing sites, excavations, quarries and open-pit mines, canals, and in the banks of dam reservoirs during periods of rapid draw-down. Since anthropogenic activity is often a localized factor it has not been considered in the national landslide susceptibility modelling.

6. LANDSLIDE SUSCEPTIBILITY MAPPING

Landslide susceptibility maps simply provide an indication of areas where landslides may form by ranking the slope stability of an area into categories that range from stable to unstable (Anon, 2011. USGS website). The landslide susceptibility maps of South Africa identify areas of potential slope instability without any indication of likely temporal occurrence or recurrence intervals. This map is therefore a preliminary indicator of landslide susceptibility and is not a design tool that can replace detailed site-specific investigations.

The national-scale landslide susceptibility assessments for South Africa used the bivariate statistical analysis and weights of evidence/logistic regression method. The eight causal factors (CF) considered at the national mapping scale include slope angle, relative relief, rainfall, lithology, seismicity, terrain morphology, dolerite contact zones and lineaments (Fig. 6). Fairly localized factors affecting slope instability such as anthropogenic activity, slopes concordant with steep bedding planes, erosion and irregular flash flooding were not incorporated in the national landslide susceptibility assessments.

6.1 Bivariate Statistical Analysis

In the bivariate statistical analysis, as described by Soeters and van Westen (1996), the individual CF maps are combined with the landslide inventory data to give weighting/ranking values per CF sub-class based on landslide densities. The landslide inventory was compiled by integrating data collected in previous CGS landslide research projects (Fig. 7). Using GIS, landslide point counts were calculated for each sub-class present in the CGS studied regions defined by the inventory data (Fig. 7). Landslide density (L_{den}) based on arithmetic density was then calculated by the following formula:

$$\boxed{\mathbf{L_{den} = Number\ of\ landslides\ in\ sub\text{-}class_a\ /\ Total\ area\ of\ sub\text{-}class_a}}$$

Density graphs of each CF were plotted and categorised to facilitate the assessment of ranking values (Fig. 8). Ranking values of 1, 2 or 3 were assigned relative to the position of each sub-class on the density graph (Fig. 8 and Table 1), where a value of 3 represents areas of highest landslide susceptibility. In ArcGIS Spatial Analyst 9.3 the slope angle, relative relief, geology, rainfall, terrain morphology and seismicity raster datasets were reclassified on a scale of 1 to 3. Dolerite contact zones and lineaments layers were acquired as polylines, therefore their subsequent raster maps were reclassified to create ranked maps based on data presence or absence whereby values of 3 or 0 were assigned respectively.

A multi-criterion decision making tool, Analytical Hierarchy Process (AHP), aided the bivariate statistical analysis in the assessment of the national-scale landslide susceptibility. This mathematical technique has been used in numerous studies to determine the relative weights among decision elements for landslide susceptibility assessments (Esmali and Ahmadi, 2003; Komac, 2006; Yalcin, 2008; Singh, 2009). The AHP uses the mathematical pair-wise comparison technique for deriving importance values (Saaty 1980, 1986, 1995). In this study, landslide experts were required to respond to pairwise comparison questions asking the relative importance of *factor A* over *factor B* (Table 2). A web application (www.cci–icc.gc.ca/tools/ahp/index_e.asp) based on Saaty's AHP model was utilised to evaluate weights and consistency ratios (CR) for all preference rating values derived from completed questionnaires.

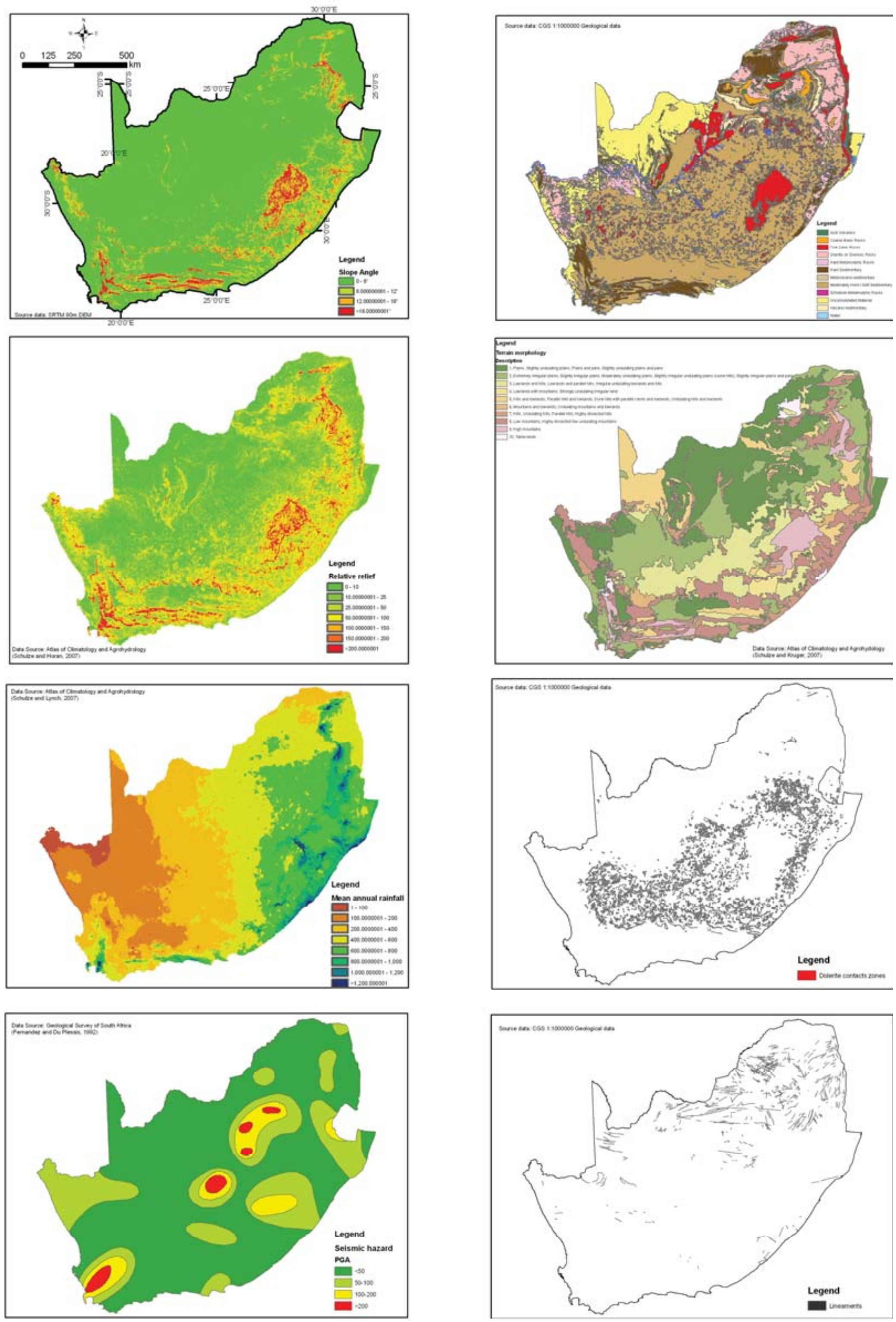


Figure 6 A compilation of the various national landslide causal factor maps. Data sources: SRTM 90m DEM, South African Atlas of Climatology and Agrohydrology, Geological Survey of South Africa, Council for Geoscience 1:1 000 000 geological data.

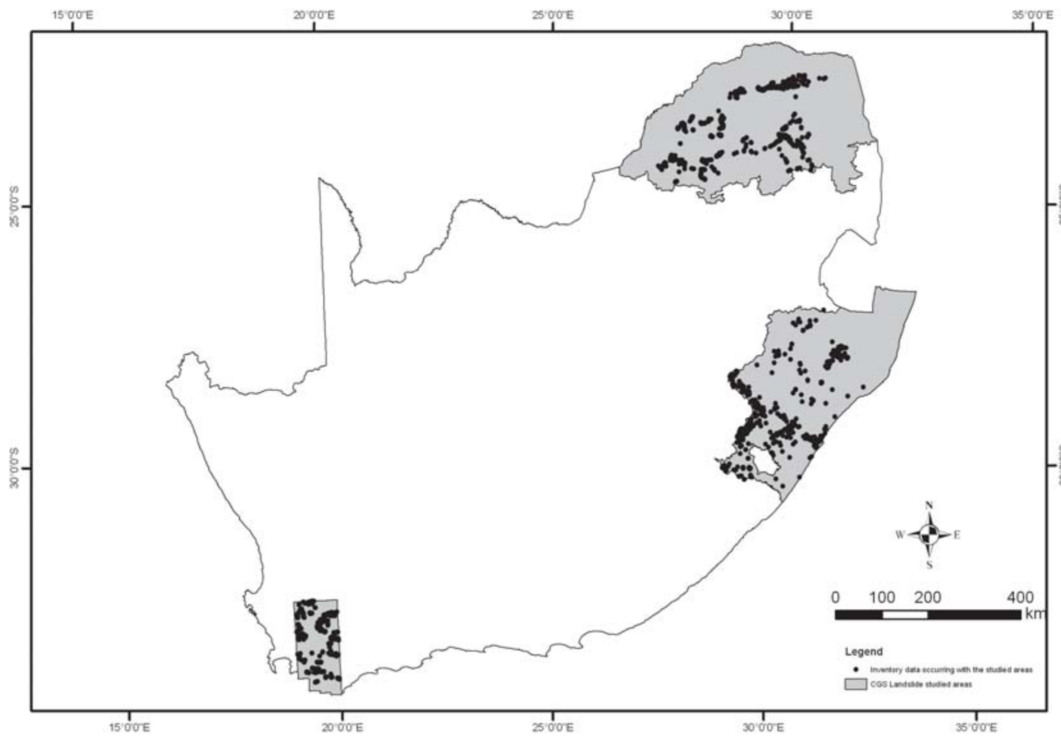


Figure 7 Map showing the inventory data in the areas studied by CGS researchers.

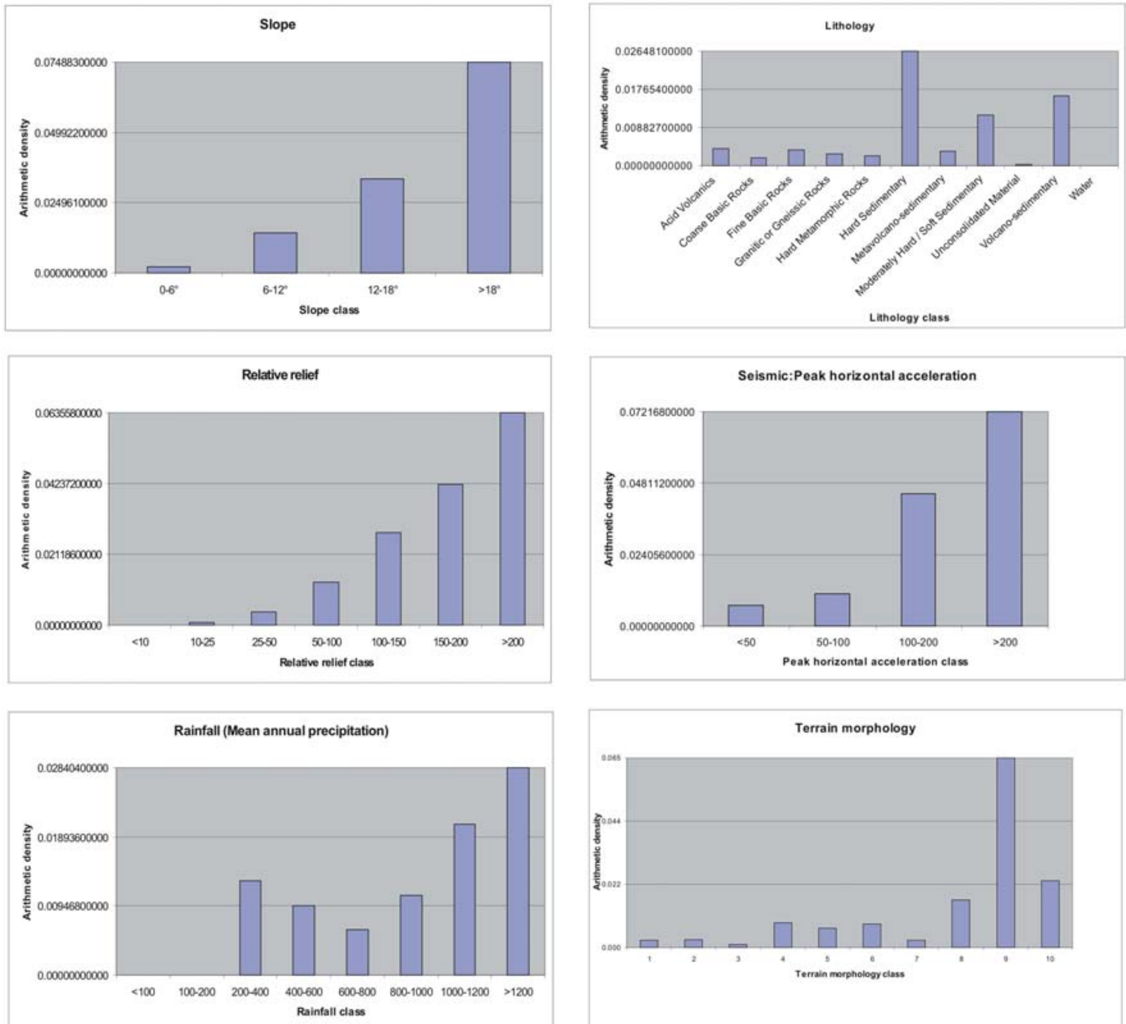


Figure 8 A compilation of graphs showing ranking values of all considered landslide causal factors.

Table 1 Ranking values of sub-classes of the various landslide causal factors

Gridcode	Slope class (degrees)	Landslide point count	Area (km^2)	Arithmetic density	Ranking value	
1	0-6°	325	155391.887	0.002	1	
2	6-12°	681	47548.543	0.014	1	**Slope Angle**
3	12-18°	728	21802.485	0.033	2	
4	>18°	633	8453.043	0.075	3	
Gridcode	**Relative relief class (m)**	**Landslide point count**	**Area (km^2)**	**Arithmetic density**	**Ranking value**	
1	<10	2	32640.405	0.000	1	
2	10-25	55	63983.293	0.001	1	
3	25-50	181	46184.561	0.004	1	**Relative Relief**
4	50-100	641	50138.127	0.013	1	
5	100-150	629	22857.501	0.028	2	
6	150-200	397	9443.832	0.042	2	
7	>200	462	7269.079	0.064	3	
Gridcode	**Mean Annual Precipitation class (mm)**	**Landslide point count**	**Area (km^2)**	**Arithmetic density**	**Ranking Value**	
1	*<100				1	
2	100-200	0	603.891	0.000	1	
3	200-400	365	28346.771	0.013	2	
4	400-600	857	89944.363	0.010	1	**Rainfall (MAP)**
5	600-800	360	57629.830	0.006	1	
6	800-1000	465	42522.976	0.011	2	
7	1000-1200	237	11462.218	0.021	3	
8	>1200	83	2922.114	0.028	3	
Gridcode	**Peak horizontal acceleration class (cm/s^2)**	**Landslide point count**	**Area (km^2)**	**Arithmetic density**	**Ranking value**	
1	<50	1102	159573.260	0.00690591896	1	
2	50-100	697	63745.923	0.01093403263	1	**Seismics (PHA)**
3	100-200	238	5336.707	0.04459678852	2	
4	>200	330	4572.642	0.07216834978	3	
Gridcode	**Lithology class**	**Landslide point count**	**Area (km^2)**	**Arithmetic density**	**Ranking value**	
1	Acid Volcanics	12	3033.957	0.004	1	
2	Coarse Basic Rocks	10	5644.200	0.002	1	
3	Fine Basic Rocks	89	24419.954	0.004	1	
4	Granitic or Gneissic Rocks	174	63568.287	0.003	1	
5	Hard Metamorphic Rocks	14	6148.382	0.002	1	
6	Hard Sedimentary	1146	43275.299	0.026	3	**Geology (Lithology)**
7	Metavolcano-sedimentary	9	2655.363	0.003	1	
8	Moderately Hard / Soft Sedimentary	810	68912.091	0.012	2	
9	*Schistose metamorphic				1	
10	Unconsolidated Material	2	8241.818	0.000	1	
11	Volcano-sedimentary	101	6268.220	0.016	2	
12	Water	0	953.051	0.000	1	

*A ranking value of 1 was assigned to sub-classes that are present in South Africa but absent in the subsidiary study area.

When using weights derived from AHP only those with acceptable consistency ratios (CR) should be considered since human subjectivity may result in inconsistent decision making (Saaty, 1986). Mean preference rating values (Table 2) were therefore calculated using only the inputs that initially produced acceptable CR values of ≤ 0.10. Subsequently, these mean preference rating values were used to evaluate weights for the various regional CF maps (Table 3). The resultant weighting values indicate that on a regional basis, slope angle and relative relief are the most significant landslide CF in South Africa (Table 3 and Appendix 1)

Table 2 Preference rating values that were considered in the landslide susceptibility assessment

Number of Decision elements	Relationship			Decision maker 1	Decision maker 2	Decision maker 3	Sum	Mean
	Factor A		*Factor B*					
1	Slope Angle	vs	Relative relief	3	5	1	9	3
2	Slope Angle	vs	Rainfall	7	7	7	21	7
3	Slope Angle	vs	Geology	5	5	5	15	5
4	Slope Angle	vs	Seismics	9	9	5	23	8
5	Slope Angle	vs	Terrain morphology	5	5	5	15	5
6	Slope Angle	vs	Dolerite contact zones	7	7	5	19	6
7	Slope Angle	vs	Lineaments	9	9	7	25	8
8	Relative relief	vs	Rainfall	5	3	3	11	4
9	Relative relief	vs	Geology	3	5	5	13	4
10	Relative relief	vs	Seismics	7	7	5	19	6
11	Relative relief	vs	Terrain morphology	1	3	5	9	3
12	Relative relief	vs	Dolerite contact zones	5	5	5	15	5
13	Relative relief	vs	Lineaments	7	7	5	19	6
14	Rainfall	vs	Geology	-3	-1	-3	-7	-2
15	Rainfall	vs	Seismics	3	5	-3	5	2
16	Rainfall	vs	Terrain morphology	-1	-3	1	-3	-1
17	Rainfall	vs	Dolerite contact zones	1	3	1	5	2
18	Rainfall	vs	Lineaments	5	3	3	11	4
19	Geology	vs	Seismics	3	5	1	9	3
20	Geology	vs	Terrain morphology	1	-1	1	1	1
21	Geology	vs	Dolerite contact zones	-1	1	1	1	1
22	Geology	vs	Lineaments	7	3	5	15	5
23	Seismics	vs	Terrain morphology	-5	-5	3	-7	-2
24	Seismics	vs	Dolerite contact zones	-3	-3	3	-3	-1
25	Seismics	vs	Lineaments	1	1	7	9	3
26	Terrain morphology	vs	Dolerite contact zones	-3	3	-3	-3	-1
27	Terrain morphology	vs	Lineaments	5	5	3	13	4
28	Dolerite contact zones	vs	Lineaments	1	1	3	5	2

Table 3 Weighting values of each landslide causal factor

Landslide causal factors	Weight values
Slope angle	0.3912
Relative relief	0.2306
Rainfall	0.0761
Geology	0.0937
Seismicity	0.0465
Terrain morphology	0.0788
Dolerite contact zones	0.0571
Lineaments	0.0261
Total (Sum)	**1.000**

The raster calculator of ArcGIS Spatial Analyst 9.3 facilitates map algebra and was utilised for the evaluation of national-scale landslide susceptibility. The landslide susceptibility coefficient (M) for each pixel was calculated using the expression:

$$\boxed{M = (0.3912X_1 + 0.2306X_2 + 0.0761X_3 + 0.0937X_4 + 0.0465X_5 + 0.0788X_6 + 0.0571X_7 + 0.0261X_8)/1}$$

6.1.1 Map description

The landslide susceptibility map of South Africa (Fig. 9) derived by the bivariate statistical analyses methodology uses a green-red colour ramp that relates to potentially stable (green), moderately stable (yellow-orange) and unstable areas (red) as described below (modified *after* R Ahmad, 2001):

Low landslide susceptibility: Within these areas there is a low potential to adversely influence slope stability. These are often associated with shallow 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 classified version of this landslide susceptibility map (Fig 9-bottom) comprises high landslide susceptibility zonal areas totalling approximately 82 600 km^2 which is generally unsuitable for spatial development (Table 4). Generally, these high susceptibility zones include steep slope areas, high relief mountain lands and deeply incised river valleys. This map highlights distinct high landslide susceptibility regions in South Africa which coincide with mountain ranges such as the uKhahlamba-Drakensberg, Lebombo, Biggarsberg and Balelesberg in KwaZulu-Natal; Soutpansberg, Lebombo and Waterberg in Limpopo; Drakensberg in Mpumalanga; Kuramanheuwe, Namaqualand escarpment and Roggeveld Mountains in Northern Cape; Drakensberg, Sneeuberge, Winterberge and Baviaanskloof in Eastern Cape; as well as the Cape Fold Belt mountains in Eastern and Western Cape.

Table 4 Areal extents of various landslide susceptibility zones in South Africa

Landslide Susceptibility Zone	Area (km^2)
Low	1012030
Moderate	122188
High	82600

Areas that have moderate slope instability potential comprise ~10% (122 188 km^2 in Table 4) of the country and are often characterised by slopes with moderate gradients. Areas like in Gauteng, North West and Free State that have shallow slope gradients but are associated with high seismicity have been clearly zoned as areas of moderate slope instability. Approximately 83% of South Africa is associated with low landslide susceptibility. The low landslide susceptibility zones, covering an areal extent of ~1 012 030 km^2 (Table 4), are generally characterised by shallow slopes forming broad plains in most parts of the Karoo interior.

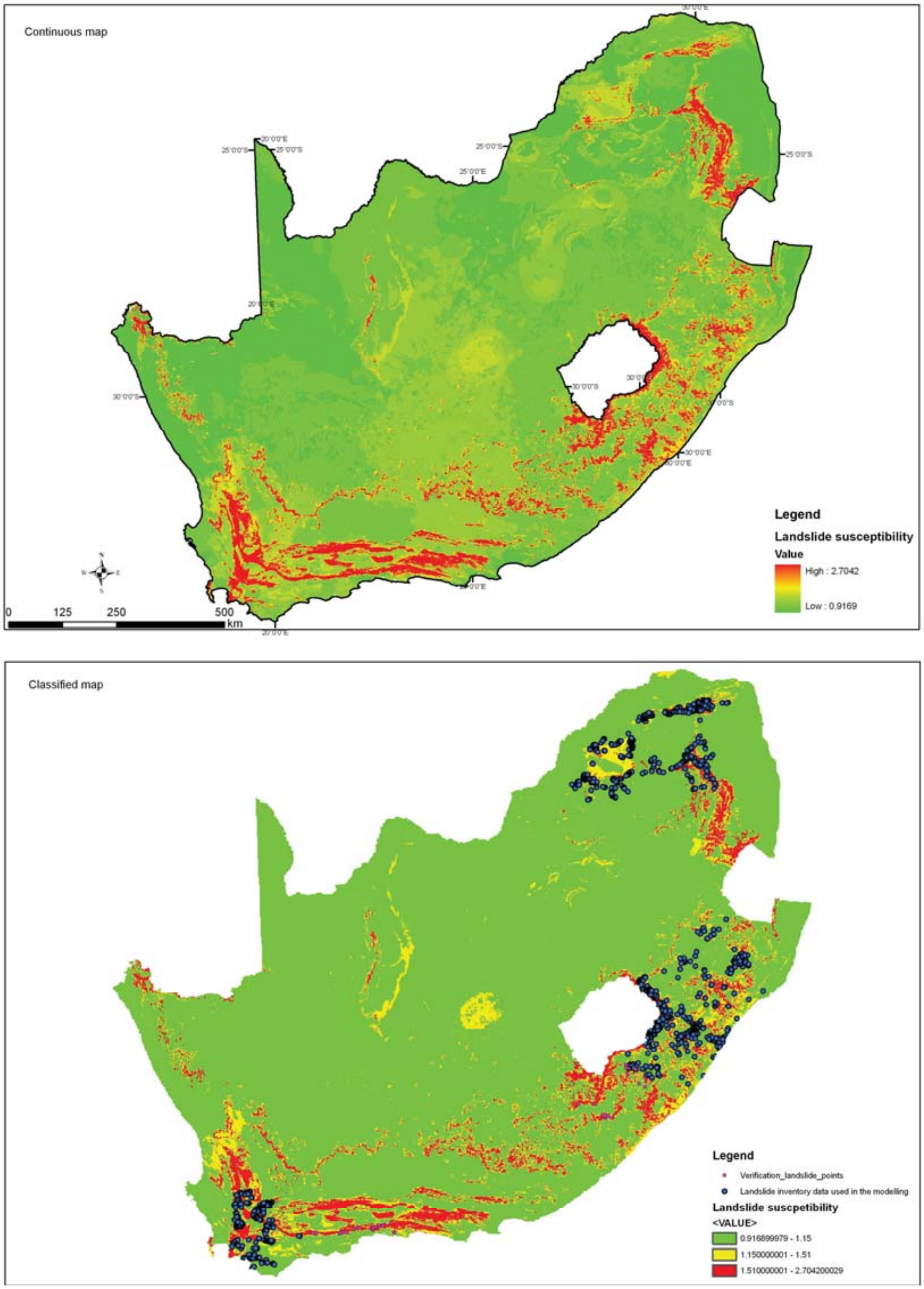


Figure 9 Landslide susceptibility map of South Africa was evaluated using the bivariate statistical method. (Top: continuous landslide susceptibility map and bottom: classed landslide susceptibility map)

6.1.2 Verification

According to Chung-Jo and Fabbri (2003) the accuracy of landslide susceptibility models can be validated by the comparison of the predicted results with the occurrence of other known landslides (verification/test sites). These verification landslides have been mapped but not incorporated in the modelling procedure. A total of 65 verification sites located in the Eastern and Western Cape provinces were remotely mapped using Google Earth™ and/or aerial photographs. These verification landslides were utilized in quality testing of the national-scale landslide susceptibility map. The landslide susceptibility map gives a fair confidence level with the distribution of 52 (80%) verification landslide sites occurring within the high landslide susceptibility zone and less than 5% falling within the low susceptibility areas comprising generally gentle slopes (Table 5 and Fig. 10).

Table 5 Landslide verification point counts in various landslide susceptibility zones

Landslide susceptibility class	Landslide verification point count
Low Susceptibility	2
Moderate Susceptibility	11
High Susceptibility	52

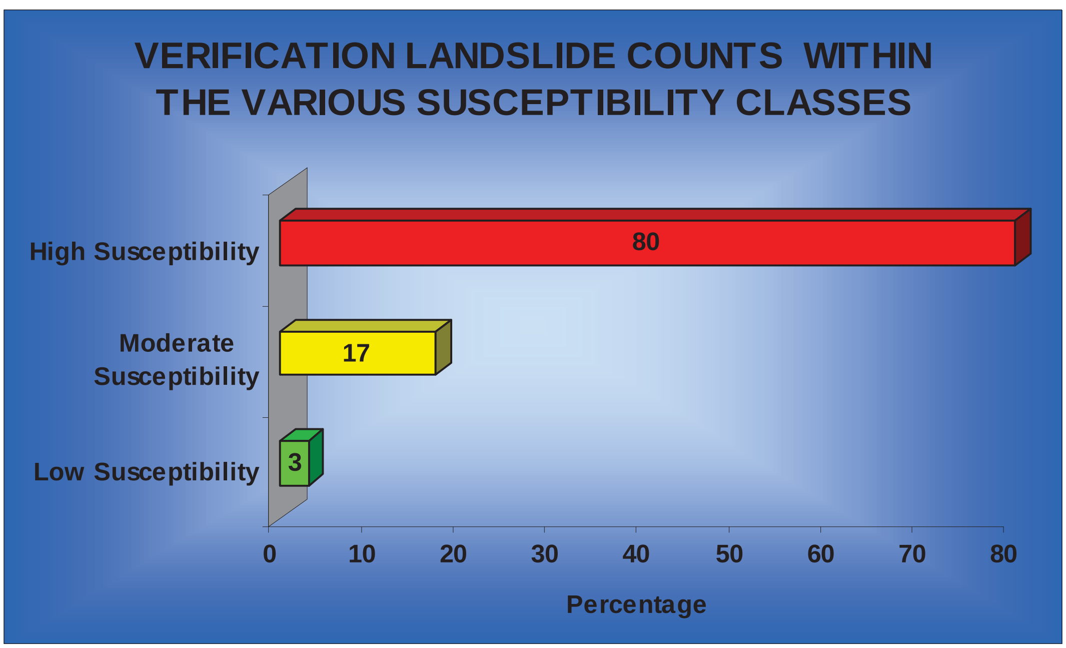


Figure 10 Graph showing percentage landslide verification counts within various susceptibility classes.

The overall quality/accuracy of the landslide susceptibility map created in this study using the bivariate statistical methodology was examined by overlaying the entire CGS landslide inventory data. This map overlay yielded a strong correspondence (Fig 9).

6.2 Weights of Evidence (WOE) / Logistic Regression method

The second methodology applied in this study, namely the weights of evidence (WOE) / Logistic Regression method is explained in the following section. This approach has been widely used in landslide susceptibility mapping. Regmi et al (2010) for example discussed the modelling of landslide susceptibility using the WOE approach for Western Colorado in the USA. The datasets used included geology, land cover, soil, topography, runoff and proximity to rivers. Neuhäuser and Terhorst (2007) applied this approach to landslide susceptibility assessment in SW Germany. The parameters used were soil, geology, topography and hydrogeology. Dahal et al. (2008) applied WOE to landslide hazard mapping in the Lesser Himalaya of Nepal. Datasets used included slope, aspect, relief, soils, geology, landuse, rainfall and distance to roads.

6.2.1 Weights of evidence approach

The weights of evidence approach is a statistical method based on Bayes' Theorem and is included in the ArcSDM open source ArcGIS add-on (Bonham-Carter *et al.*, 1990). It enables the combination of evidence in support of a hypothesis. The hypothesis being investigated in this case is; *"this location is a potential landslide point"*.

The evidence consists of the geological and physical factors that affect the occurrence of landslides. The locations of known landslide points are required as input. For each evidence (or map/layer), a pair of weights is calculated. The weights measure the association between known landslide locations and values of the maps/layers used as evidence. The hypothesis is repeatedly tested evaluating all possible locations on the map for favourability. The result is a potential map in which the evidence from the different map layers is combined.

This approach provides an objective assignment of weights, it can handle missing data, it measures some aspects of uncertainty that can be mapped and multiple factors can be simply combined. The inputs required include a study area, a training set/points; and a set of evidential data layers defining the evidence (for example geology and rainfall).

To illustrate how the weights are created, suppose we have an evidence theme which is geology and we call it B. Let the following suffice:

N (T) = the study area in unit grid cells

N (D) = the number of training sites in the study area

N (B) = the area of unit cells where the lithology is present

N ($\bar{B}$) = the area of unit cells where the lithology is absent

Then:

$$N(B) + N(\bar{B}) = N(T) \text{ (if there is no missing data)}$$

N ($B \cap D$) = training points on the area where lithology is present

N ($\bar{B} \cap D$) = training points not in the lithology areas

The following weights are then calculated:

- W+ -weight for points inside the lithology
- W-Weight for points outside the lithology
- 0 -Weights for areas of no data

$$W+ = \ln \left\{ \frac{N(B \cap D) / N(D)}{[N(B) - N(B \cap D)] / [N(T) - N(D)]} \right\}$$

$$W- = \ln \left\{ \frac{N(\bar{B} \cap D) / N(D)}{[N(\bar{B}) - N(\bar{B} \cap D)] / [N(T) - N(D)]} \right\}$$

The illustrated example considered the case when the evidential layer has only one class. Multi-class layers can be used but having too many classes can result in unrobust estimates of the weights. Positive values of W+ show a positive correlation between the training data and the evidence layers. The higher that value, the more correlated they are. The more correlated classes of an evidence layer are highly weighted in creating the final susceptibility map.

Another important output from the calculations is the Contrast (C) which is given by the following formula:

$$C = (W+) - (W-)$$

The contrast gives a measure of correlation between a training point and the class of the evidential theme. The classes with high C values are the important ones and are used in creating the final susceptibility map (Corsini *et al.*, 2009).

6.2.2 Processing

The following eight evidence layers were used: geology; dolerite contact zones; lineaments; mean annual rainfall; relief; seismic hazard; slope; and terrain morphology. The influences of these parameters on the landslide susceptibility are discussed in Section 5. The classes used for the datasets are presented in Table 1. The training set was created from known areas of landslides and is shown in Figure 9. The following section discusses the results obtained

6.2.3 Results

Initially, the weights and the contrast values assigned to the different classes of the landslide causal factors are assessed. These are presented in Table 6.

Table 6 The contrasts and weights calculated for the classes for the various criteria *(refer to Table 1 for description on the classes)*

Factor	Class	No of points	W+	W-	Contrast
Geology	1	10	-0.6844	0.0041	-0.6885
	2	10	-1.1286	0.0088	-1.1374
	3	98	-1.0865	0.0869	-1.1734
	4	202	-0.2560	0.0271	-0.2830
	5	15	-1.0708	0.0121	-1.0829
	6	1149	**1.6806**	-0.5547	**2.2353**
	7	10	0.0236	-0.0001	0.0237
	8	815	-0.3500	0.2410	-0.5911
	9	0	0.0000	0.0000	0.0000
	10	1	-5.7673	0.1419	-5.9092
	11	100	0.5538	-0.0182	0.5721
	12	0	0.0000	0.0000	0.0000
Dolerite contact zones	0	2407	0.0047	-1.5632	1.5679
	3	3	-1.5632	0.0047	-1.5679
Lineaments	0	2409	0.0005	-0.8222	0.8228
	3	1	-0.8222	0.0005	-0.8228
Rainfall	1	0	0.0000	0.0000	0.0000
	2	0	0.0000	0.0000	0.0000

	3	374	-0.5452	0.1429	-0.6881
	4	849	0.3069	-0.1343	0.4412
	5	378	-0.1564	0.0320	-0.1883
	6	458	**1.0185**	-0.1397	**1.1581**
	7	257	**1.8335**	-0.0956	**1.9290**
	8	94	**2.2682**	-0.0357	**2.3039**
Relief	1	4	-4.9093	0.2532	-5.1625
	2	48	-2.7337	0.3459	-3.0796
	3	173	-1.0030	0.1433	-1.1463
	4	695	0.5961	-0.1672	0.7633
	5	599	**1.3315**	-0.2179	**1.5493**
	6	394	**1.7474**	-0.1496	**1.8970**
	7	497	**2.3433**	-0.2110	**2.5542**
Seismic hazard	1	1091	-0.4161	0.5576	-0.9737
	2	722	0.2310	-0.0847	0.3157
	3	261	0.6259	-0.0550	0.6809
	4	334	**2.0869**	-0.1320	**2.2189**
Slope	1	296	-1.8216	1.2929	-3.1145
	2	673	0.6842	-0.1756	0.8598
	3	742	**1.4967**	-0.2966	**1.7933**
	4	699	**2.2379**	-0.3111	**2.5490**
Terrain morphology	1	165	-1.3763	0.2454	-1.6217
	2	120	-1.4327	0.1829	-1.6157
	3	18	-2.8774	0.1349	-3.0122
	4	42	-0.3064	0.0064	-0.3127
	5	68	-1.1060	0.0605	-1.1665
	6	58	0.5057	-0.0097	0.5155
	7	16	-1.9087	0.0391	-1.9479
	8	985	**0.9330**	-0.3502	**1.2831**
	9	766	**1.8695**	-0.3322	**2.2017**
	10	172	**2.0188**	-0.0645	**2.0833**

Of all the parameters, relative relief had the highest weights and by contrast proved to be the most influential factor. Classes from 5-7, for heights greater than 100 m, are the most positively correlated with areas of landslide susceptibility. Class 1 of relief, which represents the most low-lying areas, has the highest negative weight and contrast showing that it is negatively correlated to the known points and landslide are unlikely to occur in such area. The second most influential factor is rainfall where the classes from 6 to 8, namely high rainfall areas from 800 - >1200 mm per annum (Table 1), have high weight and contrast values (Table 6).

In terms of geology, an analysis of the contrast and weight values showed that the mapped landslides were in the Geology class 6 (hard sedimentary) with class 11 (volcano-sedimentary) also being a favourable target. The dolerite contact zones and the lineaments do not seem to be influential factors as evidenced by the low weight and contrast values.

The landslide susceptible areas are also affected by terrain morphology with classes 8, 9 and 10 being the most favourable target. These classes have high weights and contrast values. In terms of slope, areas of slopes greater that 18° are most susceptible to landslides. Seismic events do have an influence on landslide occurrence as shown by the high weight and contrast values obtained for areas with the highest seismic hazard.

The different weights assigned to the classes were then combined to produce a probability map (Figure 11). The final probability results were classified into five groups using the quantile classification in ArcMap. The probability classes assigned were: ‘very low’, ‘low’, ‘medium’, ‘high’ and ‘very high’ and the resulting map is shown in Figure 11. The red areas are highest potential areas and the blue areas have low probability of being effected by slope failure (based on the evidence provided by the data).

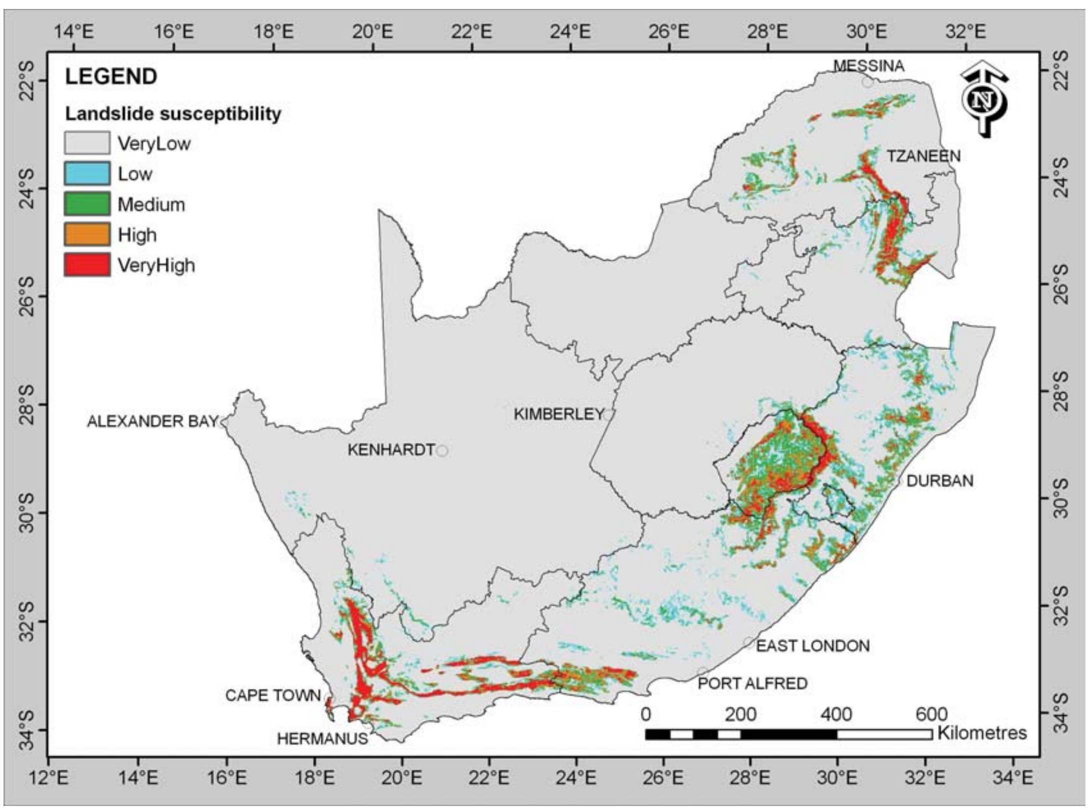


Figure 11 Map showing the probability of landslides occurring in South Africa.

6.2.4 Accuracy assessment

A test sample of landslide points that were not utilised in the WOE modelling was used in the accuracy assessment. Initially, a histogram was created to assess the number of points in each class. 67 % of the test landslide points are in the high and very high classes (Fig 12).

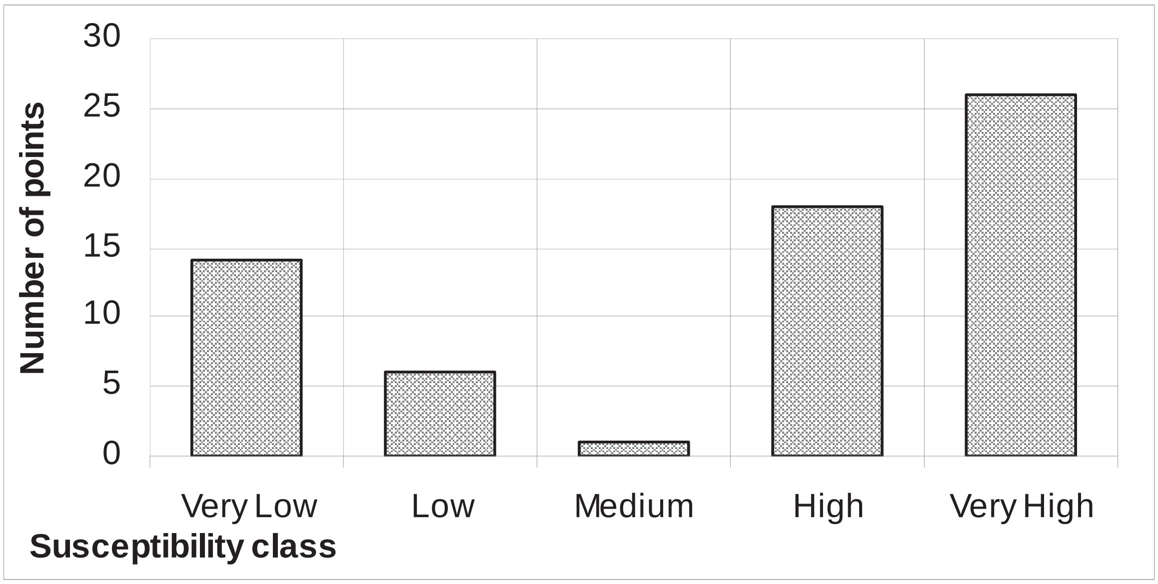


Figure 12 Number of test points in each landslide susceptibility class.

Another assessment technique called the error rate can be used as a measure of model performance. It is the total proportion of landslide points that are classified as non-landslides (false negatives) and of the number of non-landslide points classified as landslide (false positives). The landslide points falling in the very low to low categories are classified as false negatives and based on these, the error rate is 31 % (Brenning, 2005). Other assessment methods include the Receiver-operating characteristic curve (ROC) and the prediction rate curve (Sterlacchini, *et al.,* 2011; Bălteanu *et al.,* 2010). These methods are more useful in comparing between different models and were not explored in this phase of the project.

7 LANDSLIDE EFFECTS AND REMEDIATION COSTS

Landslides effect both built-up and natural environments (Highland and Bobrowsky, 2008). Their onset varies from slow down-slope creep (<60mm/yr) to very rapid high velocity and destructive events (>3m/s), in which short and long distance movements of dispersed or terrain channelled materials occurs. Transportation routes, rigid pipelines and negligibly reinforced masonry structures are thus most susceptible to damage caused by these movements. Slow movements do however allow for structure remediation and slope movement mitigation efforts, as well as safe escape. Deflection tolerances of infrastructure varies such that rail line functionality for example, is more susceptible to small local movements than are roads. Temporary, long term or even permanent commercial route closure can also occur as a result of mass movements.

In the natural environment mass wasting is a normal feature of erosion cycle processes that constantly modify the earth's surface morphology. They block rivers, alter shorelines and continental margins (sub-marine slides), exacerbate soil erosion and destroy local wildlife and flora habitats. These events impact on mankind through catastrophically failing landslide dams, sterilization of developable lands and required additional planning and design needed to traverse or remain adjacent to such terrain.

Before considering the outcome and related costs of landslide events it is important to differentiate between the timing, purpose and objectives of remediation and mitigation responses and to understand the following response concepts:

(i) *Remediation* in the landslide context refers to activities with the express purpose of clearing debris, restoring damaged infrastructure (housing, facilities, river channels, road, railway, power lines, pipe lines etc), the repair and restoration of damaged infrastructure and immediate but short term activities to check or constrain further slope movement.

Inputs from initial assessments of causal factors and possibly also of early analyses of optimal stabilizing techniques or solutions, can greatly assist in the remedial plan of action.

(iii) *Mitigation* on the other hand encompasses medium to long term strategies, revised land-use policies, public awareness programs as well as engineering approaches and designs to reduce, moderate or largely prevent further or potential future damage in the form of human and financial losses due to mass movement occurrence. It can often include some remediation activities, but in the disaster management cycle it normally follows careful planning, landslide mapping, weighing of options and designs, plus careful risk and cost benefit analysis. Put succinctly it is defined as "any sustained action taken to reduce and eliminate long-term risk to life and property" (Machan, 2006).

There are basically three forms of response to landslide events, namely:

(1) *Level of action: Avoidance*

Authorities declare "no build" or "open space" zones in landslide prone areas, to avoid unnecessary risk and wastage of public funds on costly development and possibly ongoing remediation efforts.

(2) *Level of action: Do nothing*

Usually occurs in situations where mass movements are either slow, ancient or the hazard is deemed to be benign or of no threat to society. Also when landslide characterization studies are still ongoing and a mitigation strategy is being devised.

(3) *Level of action: Remediate*

This can entail an increasing scale of activities or approaches, ranging from low level maintenance, selective stabilization to ensure immediate or short term stability, marginal remediation or even full remediation (conventional stabilization) requiring a costly and time consuming site investigation, design phase and construction works. The latter usually occurs when public safety or local or regional economic interest is at stake, or property owners deem the effort at own expense to be worthwhile, subject to authority approvals and waivers.

7.1 Landslide events in South Africa – their consequences in terms of remediation and mitigation

Available information sources indicate that twenty nine (29) people have been killed in South Africa as a direct result of mass wasting events. The Stanger earth flow killed six people in 1987 (Bell & Maud, 1996). Various rockfall events along Chapmans Peak Drive claimed the lives of five people during a 12 year period prior to its closure in January 2000 (Anon, 2003). In Ceres a rockfall event killed one person and the Merriespruit slimes dam failure which claimed seventeen lives in 1994 (Wagener, 1997).

Residential and commercial property owners, local municipalities (eg: Ethekwini), provincial (eg: Limpopo Roads Agency, Limpopo Roads department), national road authorities (SANRAL), and the national rail carrier (SPOORNET) have borne their share of landslide related costs.

Statistics in general, such as the short selection shown in Table 7, do not appear to have been widely reported in public technical documents. Recent major mitigation works undertaken along Chapmans Peak Drive and at Kaaimans Pass near George, were fortunately extensively reported on in the local press and civil engineering magazines (Frasier, 2006; Anon, 2008a & 2008b).

Successful litigation by a victim of a rockfall incident on Chapmans Peak Drive, eventually forced local authorities (Cape Metro), to close the road in January 2000 and institute a very extensive and costly mitigation program that focused on a 3km section of its 11km length. The scenic route along the Cape Peninsula coastline was first opened in 1922 and over its 80 year lifespan had experienced intermittent rockfalls. The recently completed major mitigation program entailed rock barring and pinning of the upper cliff slopes (3km), excavation and stabilization of a half tunnel (180m), construction of a reinforced concrete covered roadway section (open cantilever, 40m and semi closed section, 20m), road widening in places (for safer passage of tourist buses), small curvature corrections and installation of Swiss specification catch nets (1600m). The total cost is not mentioned in any of the three case history articles (Anon, 2004 & 2005; Krone & Ramkissoon 2004)), but was apparently in the order of R150m (Melis, 2011)

Between 2006 and 2007 Kaaimans Pass restoration and mitigation efforts, over an approximately 60 - 70 m section of mountain side highway, cost R17m. These entailed a half viaduct concrete road platform, supported on 1200mm diameter reinforced concrete piles socketed 4m into bedrock. Other work entailed rock mass and concrete structure deep stressed anchoring. In this instance the average remediation cost was just under R0.30m per metre. A summary of some other landslide occurrences and remediation/mitigation activities in South Africa is presented in Table 7.

In addition to the wide range of mass movement types already described in this report, it's worth taking into account the spatial and volumetric magnitude and potential speed of material displacements. Rock and debris avalanches off cliffs and very steep slopes, can move up to 140-200km/hr on a cushion of entrained air, while slurry-like debris flows typically move at 30-50km/hr off steep terrain. The greater the speed at which a landslide travels, the greater the potential damage it can cause.

Table 7 Landslide occurrence and remediation/mitigation in South Africa

Province	Event	Date	Damage	Remediation efforts and costs	Mitigation program and costs when available
KwaZulu-Natal	Circular slip: N3 highway. Rickivy PMBurg. (Maurenbrecher, 1975)	1973	-partial highway closure	-highway re-alignment, drainage, piles, toe loading. (no data)	ongoing monitoring by KZN Roads Dept & SANRAL. (<R5000 est)
	Earth flow: brick housing. Marian Hill, Durban. (Bell & Maud, 1996)	date unknown	-car and garage destroyed -residence damaged	rebuild. (no cost data)	(no cost data)
	Debris flow: rural house near Stanger. (Bell & Maud, 1996)	1987	-6 deaths -house obliterated	none. (no cost data)	avoidance anticipated (no cost data)

	Harrismith: Main Durban-Jhb rail line. Earth slip in thick colluvium. (Anon,2001)	1999/2000	-railway tracks displaced 500mm vertically. over approx. 350m long section. Cracks 130m upslope of tracks also.	Options: -pipe jacking R2.3m -anchors R7.7m to R9.3m -soil nails & jacked drainage pipes R9.9m -other configurations R10m-R11m Low cost jacked drainage + anchors selected. (R1.4m + R5.6m) (ie: R20000/m)	SPOORNET Ongoing monitoring (no cost data)
Gauteng	Earth flow: N14 highway Krugersdorp.	1977	-highway lane closure	Toe loading, reinforced earth structures. (no cost data)	possible ongoing monitoring by Gautrans & SANRAL. (<R5000 est.)
	Translational block slide Bruma lake. Housing complex. (Forbes, 2001)	2000	-private residence evacuated	slope clearing, pinning, gunniting. (est R0.3m)	possible ongoing monitoring by municipality (see left)
Western Cape	Rock slide: N12 highway Outeniqua Pass. (Anon, 1999; Terblanche, 2011)	1993/94 road widening recurring	-partial road closure	gabions, retaining walls, drainage. (>R1m)	ongoing monitoring by SANRAL. (<R5000 est)
	Rock falls: Chapmans Peak Drive (Anon, 2004/2005; Krone & Ramkissoon, 2004)	1994 1997 recurring in prior years.	-temporary road closures and associated tourism losses.	slope barring, anchors, pinning, wire mesh, catch fences, half tunnel, road widening, concrete roof sections.	road closure (3yrs). For measures (left) Ongoing public awareness via signage. (R150m est)
	Rock slide: N2 highway Kaaimans Pass. (Anon, 2006/2008; Erasmus, 2007)	Aug 2006		slope barring, anchors, piles, concrete road platform (est R17m.)	ongoing monitoring by SANRAL. (<R5000 est)
Limpopo	Rock falls, mudslides N1 highway Wyliespoort Pass Soutpansberg Mts	1999/2000	-temp road closures, vehicle damage	slope re-grading & grassing, gabions. (no cost data)	ongoing monitoring by SANRAL. (<R5000 est)
	Circular slips P278/1 (R523) highway: Wyliespoort/Thohoyandu:	1983-2000 recurring	-temporary road way restrictions	slope re-grading and toe loading gabions and sub-soil drains. (no cost data)	possibly just routine maintenance. (<R20000 est)

	Rock falls R33 highway Lephalale/Modimolle	date unknown	-temporary road way restrictions	gabions. (noted during landslide mapping in Limpopo) (no cost data)	possibly just routine maintenance (no cost data)

Note: Quoted cost data is time dependent and has not been inflated to current day values.

7.2 International context

Property damage can include dam over-topping, road and rail disruption, housing obliteration, crops destruction, watershed deterioration and increased soil erosion, temporary or permanent river damming and most importantly impact trauma injuries and crushing or suffocation deaths. A quick perspective on just the human losses caused by landslides shows that the worst recorded event was in 1920 in Kansu Province China; where an 8.6 magnitude Richter scale seismic event triggered dry loess earth flows that claimed an estimated 100 000 – 200 000 lives. (Selby, 1993). Other major tragic human losses due to a range of landslide types include 30 000 deaths in Venezuela (1999), 25500 deaths in Kashmir (2005), 23 000 deaths in Colombia (1985), 20 000 deaths in China (2008), 18 000 deaths in Peru (1970), 10 000 deaths in Honduras (1998), 1 100 deaths in the Philippines (2006), 585 deaths in El Salvador (2001), 400 deaths in Uganda (2010), 221 deaths in India (1998), 158 deaths in Taiwan (1999) and 125 deaths in Russia (2002). The USGS web page used to obtain the above statistics, only lists recent large events from 1911 to present, and the total recorded human loss for the 56 events listed totals 264455 people. Records kept by the Institute for Hazard Risk and Resilience (IHRR) and International Landslide Centre (ILC) at Durrheim University, show 83275 deaths worldwide were attributed to landslides, since 2002 (Petley, 2011).

Approximately 3000 - 8000 persons are annually killed worldwide by landslide related events according to the USGS (Anon, 2011). In the USA alone 25- 50 lives are lost per annum and landslides cause annual damages amounting to between one to two billion dollars ($1-2bn) (Anon, 2011, USGS website). This is a relatively low mortality statistic if one considers other societal hazards such as hurricanes, floods and diseases. New Zealand by contrast incurred an average of NZ $16m damage per year, due to landslides, over a recent five year period (Joyce, 2011). Statistics kept by the ILC (Petley, 2011) covering landslide deaths worldwide are shown in Figure 13.

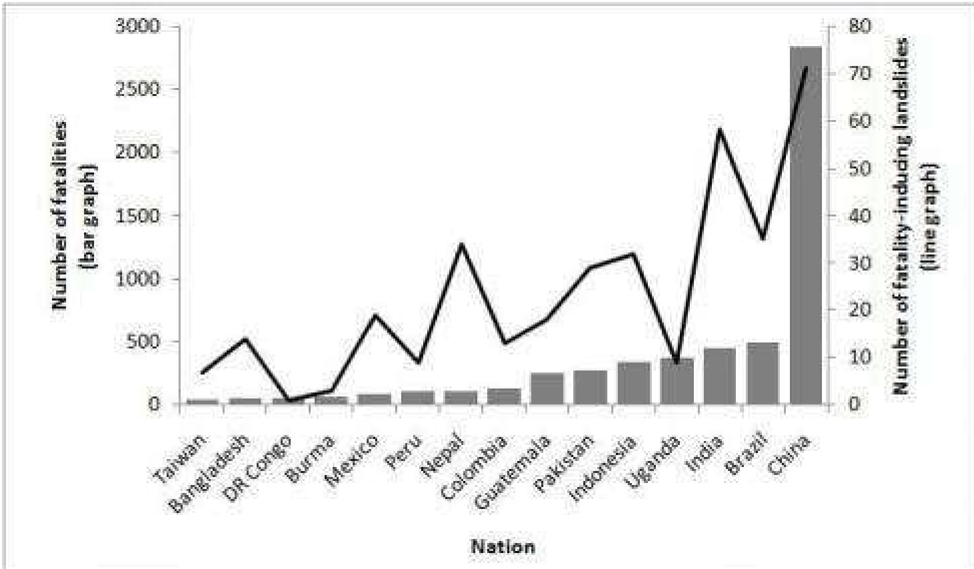


Figure 13 Graph showing landslide deaths and events for 2010 (Taken from: D Petley (2011: online site)

Some examples of how severe the monetary losses due to landslide events can be, include, Vajoint Dam overtopping due to a basin margin landslide = US $0.2bn in 2006 and 2007, Ecuador 1987: Debris flows, mudslides and deeper seated failures = US $1.0bn, Venezuela 1999: Numerous landslides and debris flows = US $1.9bn. The data presented in this study was mainly derived from the USGS web site statistics and no escalation to present $ value was performed.

A few other international examples of events, associated damages and costs of remediation and mitigation are presented in Table 8, to further emphasize the extent of landslide impacts.

Table 8 Landslide occurrence and remediation/mitigation internationally

	Event	**Date**	**Damage**	**Remediation efforts and costs**	**Mitigation program and costs**
USA	Debris flows (18000 events) San Francisco California	1982	-33 deaths -US $300m property damage	no data	no data

	Earth flow: Thristle Central Utah.	1983	-river damming -highway closure -railway closure -flooding of town	-re-alignment of road & rail routes to avoid the dam and possible future slides	-landslide dam draining -Thistle town was basically abandoned by its previous dwellers Total: US $ 600m
	Earth Flow: La Conchita California	2005	-5 deaths -coastal highway destroyed -20 homes destroyed	no data	no data
Puerto Rico	Debris slide	1985	129 lives	no data	unknown
Japan	Debris flows, mudslides, shallow slips	1958	-19754 homes destroyed	no data	unknown
Sri Lanka	Debris flows, mudslides	2003	-260 deaths -24000 homes destroyed	no data	unknown
Cameroon	Rotational & earth flows (Ayonghe, 2002)	1988-2001 11 events	-64 deaths	no data	unknown
Malawi	Debris slides Zomba Mountain	1998	-500 deaths	no data	unknown

(Note: Statistic from USGS web site unless indicated otherwise)

7.3 Examples of mitigation measures, designs and associated costs

(i) Public outreach and education:

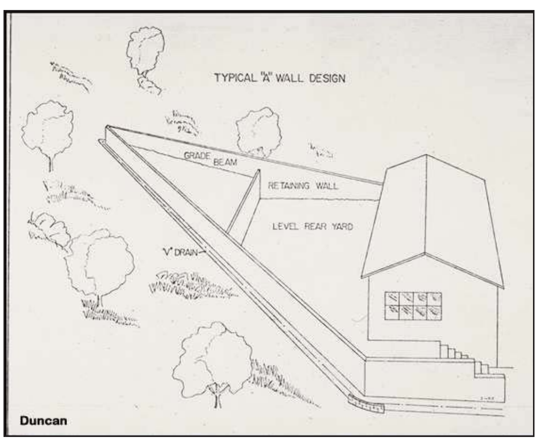
This is one of the 'soft' but relatively cheap and effective methods of mitigation. In the USA, employing a Public Outreach Official can cost upwards of $70,000 per year, but this work can also be done in part by volunteers (Anon, 2011. USGS web site). The efficacy of this approach is illustrated by the tragedy of the 1985 Amero City, Colombia event, when 23 000 deaths were caused by a volcanic eruption linked debris flow, because warnings were not passed on to inhabitants (Anon, 2011. USGS web site). Some prior public educating may have occurred in Colombia, considering it is so often plagued by such events, but as seen elsewhere in the world, people have short memories and become complacent.

Another tragic example where awareness may have prevented financial losses, is the Puget Sound (near Seattle USA) case. Ignorant residents purchasing houses along a shoreline cliff lost substantially; while the maps produced in the early 1970's detailing the risks and hazards of the area, lay almost forgotten in archives or had been disposed of. Washington Real Estate Law did not require landslide hazard disclosure at the time. In one recent instance a homeowner with a potentially US $300 000 valued home could not even sell for US $11 000, while having to still outlay US $130 000 on slope and building stabilization, on a home that is still not paid for (Anon, 2011. USGS web site).

The largest public landslide awareness effort in South Africa to date has been by SANRAL via its Slope Management System (SMS) program, initiated in 2005 (Anon, 2005). All known hot spots have been identified and properly signposted. Their annual reports in the intervening years provide some indication of SMS results and costs.

(ii) Physical barriers:

Recurring shallow landslides and mudslides affect many parts of the USA. Specially designed reinforced concrete walls, incorporating a 'V' shape as shown below, have been installed at great cost to homeowners (Fig.14a, b). Incidences of debris flows at, for example Bettys Bay, Western Cape province South Africa, would justify the incorporation of this type of mitigation measure to counter the hazard of debris flows. The South Peninsula Municipality for example (Anon, 2001), installed a range of debris flow mitigation measures at Monkey Valley in 2001, encompassing flow deflection by sand bags, gabions and geo-fabric berms, after fires devastated stabilizing natural vegetation. Liability for diversion onto neighbour's properties would also need to be considered when employing this technique.

(a) 

(b) 

Figure 14 (a) Graphic of the layout of a debris flow diversion wall. (b) Image of a viable option in specific cases.

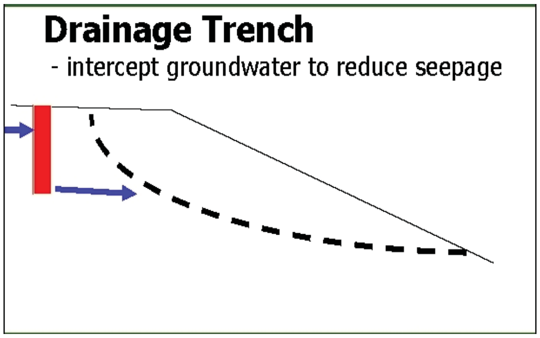
Gabions and geo-textile reinforced walls are often utilized where toe undercutting by road cuts has mobilized inherently unstable slopes (Fig. 15). Correctly engineered and installed applications have proved successful in landslide mitigation worldwide.

Figure 15 Graphic showing that poor design or maintenance of gabions can lead to recurring public fund expenditures. The images portray a slope remediation effort that was in fact a poor mitigation approach. (Limpopo Province, April 2008: Highway R518 (left and right)

PVC coated tied back gabion structures were installed on the Magoebaskloof Pass (P17/2 highway) after the January 2000 extreme rainfall event, when nearly 3000 mm rainfall was recorded for the period January/February 2000. Damages related to more than 30 landslides were repaired along a 5.5km section of road (Anon, 2002). The more costly alternative of conventional tie back anchoring was avoided through the use of this technique. Subsequent enquiries indicate a total cost of about R42m.

(iii) Drainage

Slope dewatering is usually effective in reducing destabilizing forces and improving factors of safety (Fig. 16a, b). These measures are but one facet of a slope mitigation strategy and require thorough design. Either interception and diversion of water at the slope crest, or horizontal or gently inclined drains are installed via boreholes to reduce pore pressures in the slope body or positions of possible circular failure surface formation. Large scale and costly landslide dewatering is undertaken in China and Japan for example, at large landslides, in the form of large diameter adits or deep open wells with radiating collector drains and extraction pumps.

(a) 

(b) 

Figure 16 (a) Illustration of surface water diversion to reduce the phreatric surface. This has a positive effect on shear strength. (b) As evident not all drains may be 100% functional. Borehole orientations should optimize joint intersections

(iv) <u>Slope re-profiling</u>

In the Johannesburg, Bruma Lake example shown below (fig. 17 a,b), slope flattening or block pinning should have been undertaken along the entire length of the cut when terracing for the units occurred. Only one early homeowner took this mitigation step. In this instance 18 years of stability allowed garden development on the slope. An extreme rainfall event resulted in a dip slope block glide failure. Liability accepted by the local authority cost them R300 000 to clear the unstable loose debris and gunite the resultant bare rock face. Other remediation and mitigation options were limited in this instance. It is not known if neighbours to the immediate west of the slip undertook any slope stabilization.

(a) 

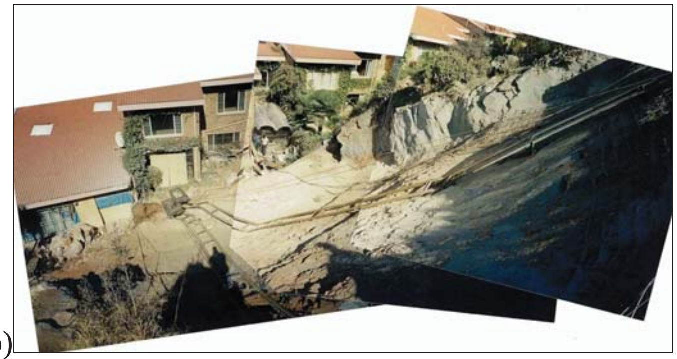
(b) 

Figure 17 (a) Graphic showing thick quartzite blocks which had slid on a gently wavy, phyllitic, bedding plane daylighting in the slope face. (Bruma Lake, Johannesburg: February 2000). (b) Image taken during post slope clearing inspection: August 2000.

(v) Wire mesh covering

The objective here is to prevent small rockfalls blocking side drains of roads or presenting a traffic hazard. Galvanized steel mesh is pinned at intervals to the rock face. Costs can be in the order of R120/m2 (North-Coombes & Moahloli, 2004) or as high as R20000/metre for 5m wide sections (Melis, 2011).

8 CONCLUSIONS

Both past and recent landslide occurrences appear to have been under-reported by various authorities and the research establishment in South Africa. This does not imply an absence of features as recent, mostly unpublished work by the Council for Geoscience, reveals a large population of events. Establishment of the full spatial record and their complete characterization is necessary as communities and formal urban growth expand unwittingly into areas prone to various forms of landslides. Landslides have also not as yet been fully identified and inventorized provincially or nationally in South Africa. Work by the Council for Geoscience is still ongoing in the Eastern and Western Cape provinces, but collation of existing data and fresh landslide mapping in the North West, Mpumalanga and the Free State provinces, has yet to commence.

The landslide susceptibility maps of South Africa derived by the bivariate statistical as well as the WOE methodologies are presented as draft maps since they need to be comprehensively ground-truthed through a fieldwork intensive phase. There is some uncertainty inherent in the landslide susceptibility results due to the data used. The broad scales of the datasets and the mapping errors limit the accuracy of the results.

It is clear that although landslides are a world wide phenomenon, they occur at varying frequencies and severity; dependent on country specific weather patterns, local lithologies, regolith profiles, relief, magnitudes and recurrence of seismic events, plus the location of urban infrastructural development and extent of land degradation. Statistics record a high ongoing annual incidence of fatalities and costly material damage globally. They are however not complete or entirely accessible as public records. Estimates indicate up to 8000 per annum direct deaths worldwide, while this is only 1person/2yrs at most, for South Africa. Countries with dense unplanned and poorly located shanty developments and vulnerable rural communities, are normally the hardest hit.

Property and indirect economic costs vary widely from millions to billions of rands, in countries of high incidence. Those with extensive modern road and rail infrastructure, such as the USA, Europe, Taiwan and Japan, naturally incur the highest losses. South African national road and rail authorities have identified most high risk areas, but possibly have not factored in the impact of abnormal weather events on presumed stable areas, or the need for pro-active mitigation at these unknown sites as well. Limited statistics indicate a cost range of R20 000/m for routine landslide stabilization using anchors and drains, which escalates to R300 000/m when major rock excavation and stabilization works are involved.

Post cleanup landslide mitigation efforts are impossible in some countries due to the sheer scale of the problem or their remoteness. The relocation and avoidance option is usually followed. Elsewhere, where land is at a premium (Japan, Taiwan, Italy, England), or vital transportation routes disrupted, one sees hundreds of millions to billions being expended on rail and highway diversions and installation of physical barriers, extensive drainage, support and monitoring systems. In South Africa road authorities have applied comprehensive remediation and mitigation strategies and techniques, to currently known or suspect key locations via their a Slope Management System (SMS).

Instances of potential mass movement are currently largely excluded and avoided for housing development via the NHBRC site geotechnical classification system and GFSH2-2002 standards. Past instances of post construction slope instability at Durban and Pietermaritzburg for example, are now checked for during geotechnical site investigation, and appropriate designs applied. However, reliable, detailed and standardized landslide susceptibility maps are still needed over many landslide prone areas of South Africa, to support ongoing local authority planning decisions and assist them in mitigating their risk to high input costs and possible recurring claims.

9 RECOMMENDATIONS

1) A mandatory standardized format and procedure of reporting to the National Disaster Management Centre (NDMC) and in turn the Council for Geoscience; by local provincial and national authorities with control over various forms of land use (road, rail, harbour, housing, agriculture), is required.

2) Landslide inventorization via collection of available statistics and susceptibility mapping programs by the Council for Geoscience needs to be more adequately funded and renewed at an expanded scale to be of relevance.

3) A comprehensive questionnaire sent to all local, provincial and national authorities, followed by selected interviews; will facilitate a far better status quo evaluation of past, present and future remediation efforts and efficacy of existing mitigation strategies.

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APPENDIX

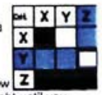
Appendix 1: Analytical hierarchy process calculations

Tools

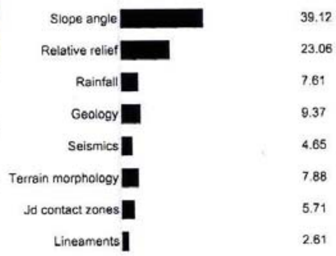
Analytical Hierarchy Process (AHP) Program

Matrix Method

Apply the desired weights to your criteria in the matrix below. Begin by finding the first criterion in the lefthand column. Follow along the row to the right until you come to the criterion you wish to compare it to, and enter the desired value. Acceptable values range from -9 (absolutely less important) to +9 (absolutely more important). After entering all of your values, click Calculate. The results will appear in the graph on the right.



Results



Consistancy Ratio: 0.039

The small matrix above provides an example. In this case, criterion Y is being compared to criterion Z. If criterion Y is absolutely less important than criterion Z, a value of -9 would be appropriate. If criterion Y is moderately more important the criterion Z, a value of +5 would be appropriate. And so on.

Importance

absolutely less | moderately less | equal (-1 or 1) | moderately more | absolutely more

-8 -7 -6 -4 -3 -2 2 3 4 6 7 8

Criteria	Slope angle	Relative relief	Rainfall	Geology	Seismics	Terrain morphology	Jd contact zones	Lineaments
Slope angle		3	7	5	8	5	6	8
Relative relief			4	4	6	3	5	6
Rainfall				-2	2	-1	2	4
Geology					3	1	1	5
Seismics						-2	-1	3
Terrain morphology							-1	4
Jd contact zones								2
Lineaments								

Calculate

Last Updated: 2005-5-13

Important Notices