Universität Hohenheim

Institut für Pflanzenproduktion und Agrarökologie in den Tropen und Subtropen
Fachgebiet Biodiversität und Landrehabilitation in den Tropen und Subtropen

Prof. Dr. R. Schultze-Kraft

Evaluation of two GIS-based Models for Landslide Prediction

Master Thesis

von

Steffen Walther
aus Netphen-Deuz

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Glossary

ArcView	Common and popular GIS processing and analysis software from ESRI.
ArcWofE	Weights of Evidence extension for ArcView. ArcWofE is a free tool for probabilistic modeling in GIS based on ArcView.
binary map	A binary map is a map containing only two classes, e.g. one class that shows a feature and one class that does not.
CIAT	Centro Internacional de Agricultura Tropical. International Center for Tropical Agriculture, Cali, Colombia.
DEM	Digital Elevation Model. A DEM is digital cartographic/geographic data in raster form and consists of an array of elevations for ground positions, sampled at regularly spaced horizontal intervals.
DGPS	Differential GPS. Differential correction is applied to a GPS to minimize errors.
ESRI	Environmental Systems Research Institute, Inc., Redlands, CA, USA.
FS	Factor of Safety. A value giving information about the stability of a defined point on a map. Calculated by SINMAP using an infinite plane slope stability function.
GIS	Geographical Information Systems. A system of hardware and software used to capture, store, process, analyze, and display geographical data.
GPS	Global Positioning System. A constellation of satellites that makes it possible for a user with a ground receiver to pinpoint his geographic location.
grid-file	ArcView terminology for data layers in raster format.
INETER	„*Instituto Nicaragüense de Estudios Territoriales*“. Nicaraguan Institute for Territorial Studies, Managua, Nicaragua.
landslide	General term describing downslope movement of soil, rock, and organic matter under the influence of gravity.
MAG	„*Ministerio Agropecuario*“. Ministry of Agriculture (today:: MAGFOR), Managua, Nicaragua.
MAGFOR	„*Ministerio Agropecuario y Forestal*“. Ministry of Agriculture, Livestock, and Forestry (earlier: MAG), Managua, Nicaragua.
raster format	In raster data, an individual value is assigned to each cell of a layer. Cell size is defined by resolution of the data.
shape-file	ArcView terminology for data layers in vector format.
SI	Stability Index. A value giving information about the probability of stability or instability of a selected point on a map.
SINMAP prediction	Stability INdex MAPping, a free ArcView extension for landslide modeling.
vector format	Data in vector format uses dynamic boundaries to define an area. Everything inside this boundary has the same value.
watershed	an area that collects and discharges runoff through a given point in a stream.

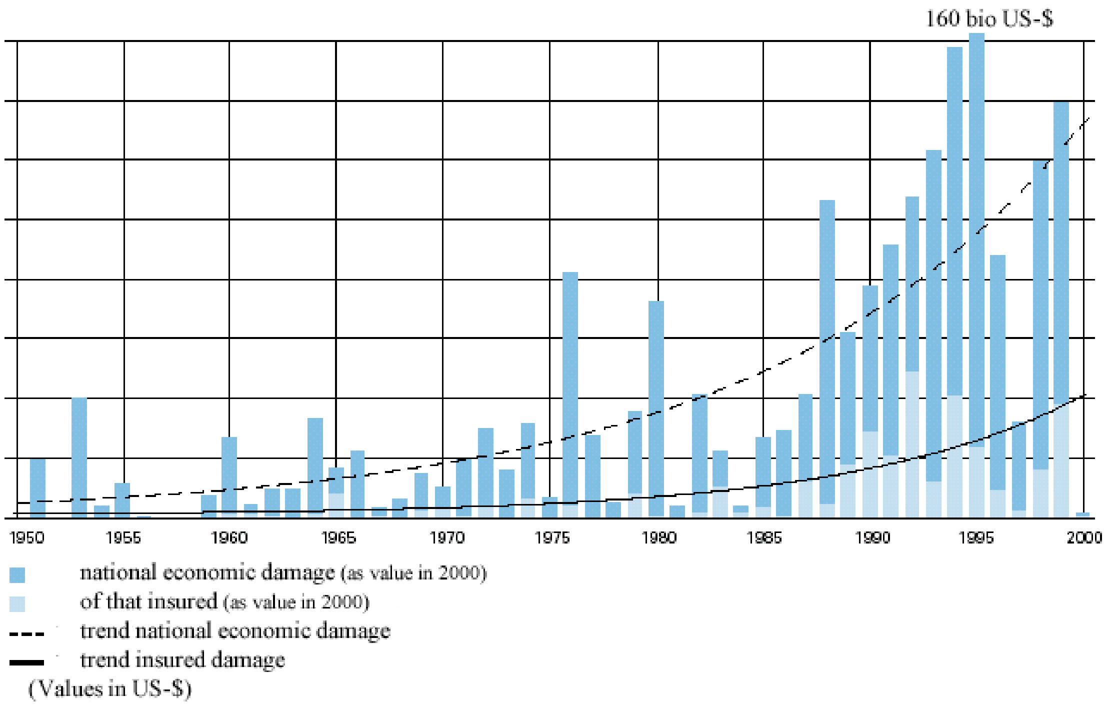
1 Introduction

In today's societies, people and organizations rely increasingly on forecasts and predictions. More and more complex systems are developed and implemented. International networks are created and maintained, linking more and more knowledge and experience. On international conferences, global goals or priorities are discussed and resources are allocated accordingly. Although generally the interests and priorities of the participating nations are diverse, and agreements on joint actions are a difficult process, a whole decade was dedicated to natural disaster reduction: The International Decade for Natural Disaster Reduction (IDNDR, 1990-1999). It was a period of intensified and accelerated international scientific exchange (WISNER, 2000) mandated by the United Nations (UN).

1.1 The Demands

Headlines about natural disasters abound all around the world. Television and gazettes show an increasing and never ending flood of pictures, where natural disasters devastate large landscapes and cause human tragedies. Connected to this, billions of Dollars (US-$) are mentioned in damage. The „*Münchener Rückversicherung*" registered a dramatic increase, not only in numbers of events, but also in economic damages over the last 50 years (MÜNCHENER RÜCKVERSICHERUNG, 2000; Graph 1, p. 2). Food security in the affected regions and even beyond is seriously on the edge. Many lives are lost due to the immediate effects and later due to health risks, including epidemics. Besides the catastrophic direct effects on the agricultural and other sectors, time and resources allocated to reconstruction are lacking elsewhere. The economy of whole countries is struggling where natural disasters of greater magnitude are loading unbearable problems on population and economy.

In many developing countries, the economy is often linked to agriculture with a high percentage of the population working in or being dependent on the agricultural sector. In 1998, Hurricane Mitch devastated large areas of Central America. Despite of high, sustained wind speeds of over 200 km/h (NCDC, 1999), it was not the winds but the associated rainfall that caused most destruction (DEWALT, 1998). In terms of agriculture, catastrophic floods and landslides damaged much of the cropland in this region. While flooding is a comparably easy to understand effect, landslides present themselves highly complex. Hills withstand decades of rains, storms, and droughts with or without human interaction and suddenly collapse. Mitch related landslides appeared all over the affected area of Central America and destroyed cropland and pastures.



(**Source:** MÜNCHENER RÜCKVERSICHERUNG, 2000.)

Graph 1: Natural disasters and economic damages. Figures and trend: 1950 to 2000.

Agricultural research is conducted frequently on-farm in representative study regions. CIAT („*Centro Internacional de Agricultura Tropical*") e.g. conducts much of its research on sustainable agricultural production in benchmark watersheds. Problematic is the issue that often no vulnerability analysis with respect to landslide occurrence exists. Geotechnical studies and engineering projects to assess and stabilize potentially dangerous sites can be costly (BC GEOLOGICAL SURVEY, 1993-7) and are very time consuming. A simple tool for landslide assessment could conclude the efforts undertaken in regard to sustainable land use planning and even give a new insight regarding future priorities. Important is that such a tool is fast, reliable, and does not demand too much energy and resources.

1.2 The Problems

Much of what is commonly called a natural disaster in the media is a natural process to many scientists, recurrent effects with a frequency of months, years, and centuries, even millennia. Problematic is the issue to differ between the natural process, related dangers and risks, and

the final catastrophe. GLADE & DIKAU (2001) address the need for a clear distinction between the terms and review definitions and explanations. Generally, they conclude, the question of when and especially for whom a natural event becomes a natural disaster is important. To classify the effects, a great amount of criteria are used.
Common criteria include:

- The number of injured people and casualties;
- The number of damaged or destroyed houses and homeless or displaced people;
- The number of damaged or destroyed infrastructure (hospitals, schools, roads, bridges, etc.);
- Influence on the national economy; and
- Costs of search and rescue activities.

These criteria, so GLADE & DIKAU (2001), ease a general comparison but are only of limited use for comparable statements. The classification of what magnitude makes a disaster out of a natural event is subjective. They conclude that a link to the affected society is necessary and follow the definition of the MÜNCHENER RÜCKVERSICHERUNG (2000) that classifies events as natural disasters „when local management capabilities are exceeded and national or international help is required to deal with the effects".

Spatial information is often readily available to run off-the-shelf, GIS-based (Geographical Information System-based) models for landslide prediction. However, most of the current modeling approaches are based on common landslide risks. Underlying parameters are e.g. derived from average rainfall distribution maps. Others use mean annual rainfall as described by BABU & MUKESH (2002). As a result, most studies do not account for landslide risks under extreme climatic events.

It is unknown how, and if, available GIS-based models or modeling approaches will account for landslide occurrences caused by extreme climatic events. In general, their data demand is rather tailored towards data describing average or common and thus expected conditions, and does not include variation as caused by extreme events. Although these events are rare, the effect often destroys in hours the work of decades, even generations. Surely, says WISNER (2000), „earthquakes and hurricanes happen. But disasters follow because of human action or inaction".

The application of different models as planned in this study diversifies and broadens the total data demand. The use of a model may depend on the applicability of the underlying theory and is of course influenced by the available data. In general, conclude also WHITE *et al.* (2002), a variety of data is generally available or easy to obtain. In many countries, great amounts of data are offered free of charge by governmental agencies or research facilities. Alternatively, high quality data in digital format can be ordered from various service providers, governmental or private.

Especially in the developing world, this can be more complicated. Data may not be available or has to be digitized. Age of the data, as well as spatial and temporal differences may pose additional problems. Digitization of data is time intensive or costly. Processing of the data, e.g. in order to create a DEM (Digital Elevation Model), may create additional software needs and is time consuming or costly too. Additionally, the models may pose special demands that are not included in the national survey programs.

OBERTHÜR (1999) points out and summarizes several problems related to the scale of available data with special regard to soil maps. Soils commonly show a large environmental variation and soil descriptions often do not account for small inclusions or variation towards the border of a mapped area (SOIL SURVEY DIVISION STAFF, 1993). The related accuracy may put the relevance of the map at question. As extreme events are infrequent, a history about past events often does not exist in the details or quality necessary. Knowledge of e.g. landslides in a region may either be not recorded or geographically referenced, making an application rather difficult. OBERTHÜR (1999) points out that local knowledge might be particularly beneficial. But already a few years after an event, the information given by local counterparts on a region or the impact observed in a region may be very subjective.

1.3 The Aims

WHITE *et al.* (2002) ask if geographic characterization and analysis in the wide field of agronomic research is insufficient. They argue that with the background of increasing availability of GIS and spatial data, increased use could be anticipated, but found that this is limited to individual fields and local landscapes. This study wants to pick up at this point and evaluate the potential of certain, generally available tools (models) when they are applied to a specific field. Nearly every program available has proven its capabilities already in various studies - but how do they account for extreme events and how useful are the results for decision makers? Different modeling approaches will be applied to compare the results and to understand their respective potentials in this regard. Deterministic and probabilistic based models hereby represent the outer edges of the spectrum.

In a first step, suitable GIS-based models for landslide prediction will be identified. Their data demand will be verified against the available data. Missing data has to be generated, wrong formats have to be converted. Generation of data is a critical issue. VAN WESTEN (2000) reminds that field surveys are often problematic in terms of cost/benefit ratio. Remote sensing data application and its limitations are explained by ZINCK *et al.* (2001). Alternatively, it has to be evaluated whether reasonable results can be expected without contributions of certain information. In this study, a field survey will be applied to determine the geographic location and some additional information about the landslides. This is possible because of the comparably limited area and manageable number of landslides observed.

Key criteria in the evaluation of the results will be accuracy and utility value. Evaluation results will determine the best method and lead to general insights in the ability of common models regarding the prediction of landslides caused by extreme climatic events. Conclusions regarding the calibration of those models can be a valuable aid when such methods are applied in future studies.

Depending on the results of the evaluation, a risk probability map for the study area will be generated.

1.4 The Approach

Looking at a wide range of effects, scientists put tremendous efforts in understanding the cause-effect relationships. The interests in the results are diverse. Scientists like to know the causes and origins, their links and dependencies. Governments and other authorities or investors like to derive planning implications. Insurance companies like to know the risks associated. Problematic in this regard is that the mechanisms involved are very complicated due to the interconnected and compounded processes. It is extremely difficult, if not impossible, to recreate the phenomena in experiments. Simulations or modeling is an interesting alternative (EARTH SIMULATOR CENTER, 2002).

With the ongoing development of computing power, of course more complex models can be realized. Systems like the „Earth Simulator“ (EARTH SIMULATOR CENTER, Yokohama, Japan), try to simulate as many factors as possible, yet even the entire relations on earth including effects of the global climatic change, with the latest state-of-the-art supercomputer. Less complex systems deal with single factors, or only a choice of combined factors, and can be run on personal computers. Climatic models e.g. simulate when and where extreme events, such as hurricanes or excessive rainfalls (or both) might occur. GLADE (1998 & 2000), CROZIER & GLADE (1999), and GLADE *et al.* (2000) address the issue of what rainfall events are landslide triggering in particular. Uncertainties of rainfall-induced landslide hazards are analyzed by CHOWDHURY & FLENTJE (2002). Other models simulate the impact of a given event, e.g. excessive rainfall, at a given locality. Examples are studies by GLADE (2000), who models the soil moisture development over a period of rainfall events with regard to landslide risks. FALL & MORGAN (2000) present and compare ecological soil moisture prediction models and illustrate basics. More complex approaches are dedicated to terrain stability mapping (Pack *et al.*, 1998a) and landslide issues (GRITZNER *et al.*, 2001; ZINCK *et al.*, 2001; QIN *et al.*, 2002), and try to combine knowledge and derive explanations for past occurrences (ZINCK *et al.*, 2001). An indication of how wide the interests in the modeling results are, is given by CROVELLI (2000), who describes the development of probability models for estimation of number and costs of landslides.

In this study, different approaches to model landslide risks are identified and evaluated with regard to their applicability and data demand. Deterministic based methods are represented by SINMAP (Stability Index Mapping; PACK *et al.*, 1998a). Deterministic models are process based approaches. SINMAP models shallow, translational landslides and can be applied to this field without geographic limitations (PACK *et al.*, 1998a & 1998b). The SINMAP approach is similar to the one used by other models frequently found in literature, e.g. SHALSTAB (Stability Modeling for Shallow Landslides; DIETRICH & MONTGOMERY, 1998) or LISA (Level I Stability Analysis; HAMMOND *et al.*, 1992) but uses a more complex understanding of a number of issues.

Probabilistic approaches calculate statistical relationships between provided input data and point data. In this study, landslides are understood as point data, following a common understanding in landslide analysis (PACK *et al.*, 1998a; BABU & MUKESH, 2002). ArcWofE (Weights of Evidence extension for ArcView; KEMP *et al.*, 1999) does not differ much from other models such as EXPECTOR, developed by CSIRO Land and Water in Perth, Australia. Main differences can be found in terms of literature coverage or the way they present themselves to the user.

A thorough review of the available data and a comparison with the data demand of the models revealed that especially for the deterministic based SINMAP approach all key input maps were readily available. Lacking information on detailed parameter values will be compensated by expert knowledge and verified with the calibration routines included in the program. Further, the assumption was made that all data taken from the CIAT database or other sources, was established according to the common standards of mapping. The input data for the weights of evidence modeling was selected based on knowledge on landslide driving factors (SATTERLUND & ADAMS, 1992; BC GEOLOGICAL SURVEY, 1993-7) and results from other landslide studies (FERNANDEZ *et al.*, 1999; ZINCK *et al.*, 2001; BABU & MUKESH, 2002). The statistical analysis is done with tools recommended and provided in the ArcWofE program.

A comparison of the results (predicted areas of risk) to the landslide points (known areas of risk) helps to identify the quality of the results. A comparison between the results of one model to the results of the other with regard to captured landslides and amount of area predicted at risk, allows conclusions about the utility value of each model when applied to this question.

Landslides

„Landslide“ is a general term to describe down-slope movement of soil, rock, and organic matter under the influence of gravity (BC GEOLOGICAL SURVEY, 1993-7). „Landslide“ is, according to GLADE & DIKAU (2001), next to „mass movement“ a generally accepted term in the English language and used to characterize the process group of gravitational mass movements. SATTERLUND & ADAMS (1992) describe it as a „generic term that includes all types of mass wastings that exhibit perceptible motion“. They note that the many subforms can be distinguished by their respective shearing failure and perceptible rate of motion. GLADE & DIKAU (2001) summarize the processes behind the mechanisms of gravitational mass movements and conclude that shallow, surface-parallel translational movements as well as rotational slope failures belong to this group. Landslides adversely affect a variety of resources, including the total or partial loss of the land. Individual landslides are caused by a variety of factors. However, some are believed to play a more important role. The nature of the underlying bedrock, the configuration and geometry of the slope, and the ground water conditions are main controlling factors. Also, landslides can result directly or indirectly from human activity. Slope failures can, e.g., be triggered by construction activity, where dangerous slopes are overloaded or undercut, and/or the surface or subsurface water flow is redirected (SATTERLUND & ADAMS, 1992; BC GEOLOGICAL SURVEY, 1993-7).

Landslide Modeling

Landslide analysis is complex and tools are increasingly computer based (BABU & MUKESH, 2002). The development of models is often target driven with regard to a certain background. Models such as LISA (Level I Stability Analysis; HAMMOND *et al.*, 1992) or SINMAP (Stability Index Mapping; PACK *et al.*, 1998a) have been created with the purpose to provide engineers and scientists a personal computer program to evaluate slope stability within planning areas in forested upland (KOLER, 1998). Other models, such as ArcWofE (Weights of Evidence extension for ArcView; KEMP *et al.*, 1999) are probabilistic models that can be applied to many questions regarding point distribution over an area. Similar modeling approaches and their application in a number of case studies can be found in the literature. Today, GIS-based models are frequent, due to the unique capabilities of a GIS to capture, store, and handle data, even referenced with spatial or geographic coordinates, and the ability to integrate appropriate engineering models (BABU & MUKESH, 2002). This is not limited to modeling or analysis. The potential of GIS's when embedded in a decision support system is illustrated by LAZARRI & SALVANESCHI (1999).

2 Materials and Methods

2.1 The Study Area

Nicaragua is among the Central-American countries that suffered serious damage and devastation during Hurricane Mitch in 1998. The San Dionisio municipality in the Department of Matagalpa, was chosen as study region because CIAT has several projects in the region. The approximate location of the study area is illustrated in Figure 1 below.

(**Source:** LONELY PLANET, 2002)

Figure 1: Map of Nicaragua.

2.1.1 Geography

The San Dionisio municipality is located approximately 150 km North-East (NE) of Managua, Nicaragua's capital city. The nearest bigger city or regional center is Matagalpa, the capital of the Department of Matagalpa („*Departamento de Matagalpa*"). San Dionisio can be reached by road conveniently; remote parts can be accessed with a four-wheel drive vehicle. The terrain, though partly rugged and steep, is reasonably accessible. However, many landslide-sites can only be reached on foot. A local organization, Campos Verdes, provided knowledgeable guides and resource persons.

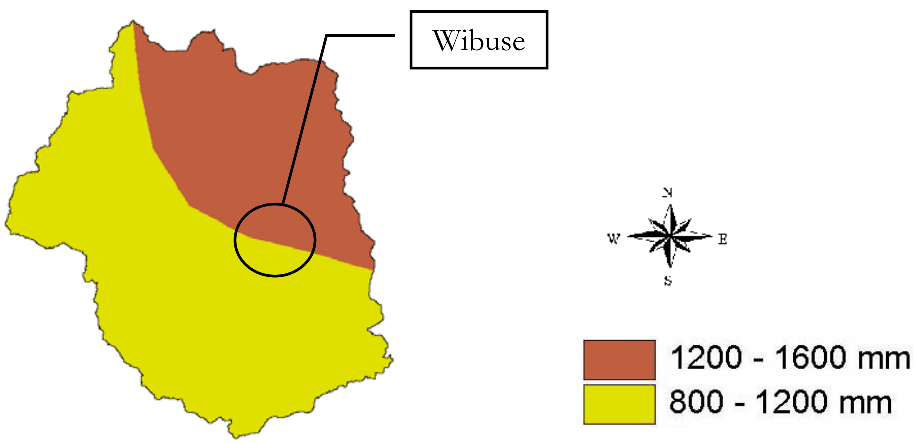
The study area is slightly larger than the San Dionisio municipality and drawn along the watershed lines. This choice was a matter of convenience and for practical reasons, as some maps were already available on this level in ArcView (ESRI, 1996a). A watershed is defined as the area that collects and discharges runoff through a given point in a stream (SATTERLUND & ADAMS, 1992). No part of it should be ignored in order to avoid a possible bias in the results. ESPINOZA & VERNOOY (1998) identified 15 sub-regions („*microcuencas*") in the selected watershed in a participative mapping approach.

The resulting study area comprises about 173 km^2. Altitude ranges from 299 m to 1266 m above sea level. Slope values are between 0 ° (flat) and 62 °. Slope is measured in degree of slope (°). The values were extracted from a 15 m digital elevation model (DEM) of the study area in ArcView.

2.1.2 Climate

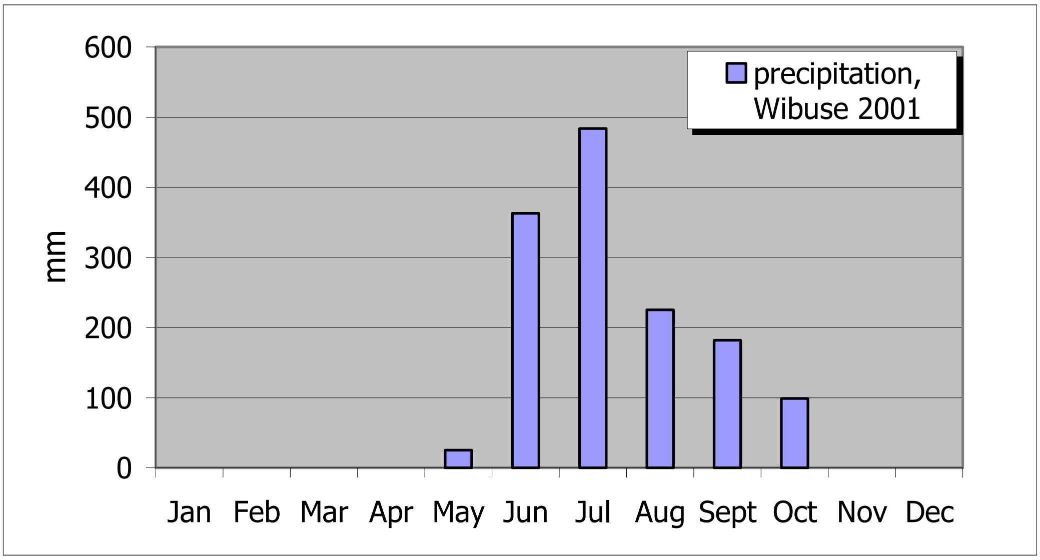
General Climate

The San Dionisio region expects annual rainfalls between 800 mm and 1600 mm (MAGFOR, n.d.). In about three quarters of the area, rainfall is 800 mm to 1200 mm; higher rainfall of 1200 mm to 1600 mm is found in the remaining region. The rainfall pattern is illustrated in Figure 2. The rainy season is usually between April and November of each year with the dry season in the remaining months. The pattern observed in Graph 2 shows the recordings for Wibuse in 2001, a so-called 'El Niño' year where rainfall was scarce and unpredictable. Direct comparison of rainfall pattern from several years is not possible due to the lack of reliable data. The approximate location of the Wibuse sub-region is indicated in Figure 2. Average temperature varies between 20 °C and 27 °C (MAGFOR, n.d.).



(**Source:** MAGFOR, n.d.)

Figure 2: Rainfall distribution in the San Dionisio watershed.



(**Source:** CIAT, San Dionisio, Matagalpa, Nicaragua.)

Graph 2: Precipitation for Wibuse in 2001. Data recorded with a rain gauge operated by CIAT on a benchmark site in Wibuse, San Dionisio.

Conditions during Hurricane Mitch

No precipitation records are available for the San Dionisio or Matagalpa region for the time of Hurricane Mitch. However the literature states that „exceptional rainfalls" occurred for six consecutive days (USGS, 1998; WMO, 1999). Amounts of up to 600 mm rain on a single day are mentioned (DEWALT, 1998) that washed away hillsides (ABRAMOVITZ & DUNN, 1998). The USGS report (1998) shows figures for Chinandega, capital of the department of Chinandega, Nicaragua, with heavy rains starting October 25 reaching up to 500 mm/day; total October rainfall summed up to 1984 mm, about six times the October average of 328 mm in normal years (USGS, 1998). While Chinandega is located close to the Pacific coast of Nicaragua (180 km North-West of Managua) and a direct comparison with Matagalpa is difficult, the magnitude of the rainfall is impressive. Matagalpa was reported amongst the most seriously affected regions in Nicaragua (WMO, 1999).

2.1.3 Soil

Information on the soils is available from two soil maps at a scale of 1 : 500,000 covering the entire study area (MAG, 1978) and 1 : 50,000 covering only part of the study area (MAGFOR, 1996a). Additional information was available for point locations from the landslide survey. Basic soil information was derived from the 1 : 500,000 scale map. The 1 : 50,000 map as well as the information from the landslide survey were used as additional information, helping to clarify soil parameters whenever the broad resolution was not sufficient. The 1 : 500,000 scale map identifies and describes six regions with different soil types by an individual identification code (ID). The ID for each region is mentioned in brackets and kept for all further analyses. The details on the soils described are derived from „Soil Taxonomy“ (SOIL SURVEY STAFF, 1999) and the „Keys to Soil Taxonomy“ (SOIL SURVEY STAFF, 1998).

Region 1 (MH-4)

The soil type in region 1 is identified as a Lithic Haplaquoll. A Haplaquoll is a Mollisol with minimum horizon development and aquic conditions. Aquic conditions are found when soils currently show continuous or periodic water saturation and reduction. Lithic refers to a shallow lithic contact; that is the boundary between the soil and a coherent underlying material. Mollisols are the soils of the steppes and extensive in subhumid to semiarid areas. They are base-rich mineral soils and usually dark colored. Mollisols frequently developed under grass at some time but also often have been forested in earlier times.

Region 2 (EC-5)

Soil type 2 is a Typic Usthorthent. An Usthorthent refers to a common Entisol with ustic moisture regime. Soils with ustic moisture regime generally have limited moisture, most of which however is available during growing season. Typic shows that the soil has no special characteristics or additional properties indicating a transition to another great group. Entisols are mineral soils that commonly show only little or no development of pedogenic horizons. This is because the soil material usually is not in place long enough to undergo pedogenic processes and form distinctive horizons. Reasons include active erosion or frequent new deposits. If the soil material is old enough to expect diagnostic horizons, it often consists of quartz or other minerals that show a high resistance to the (weathering) processes needed to form such diagnostic horizons.

Region 3 (AE-4)

The soil type identified in region 3 is a Vertic Tropudalf. A Tropudalf is an Alfisol with udic moisture regime in the Tropics. In the udic moisture regime, the soil moisture control section does not get dry in any part for a minimum of 90 cumulative days in normal years. Vertic indicates that the soil has some of the properties of a Vertisol. Typical properties of a Vertisol are a high clay content and deep, wide cracks. The soils swell when moistened, shrink when dry and show slickensides. Typical Alfisols show an ochric epipedon, an argillic horizon, and moderate to high base saturation. They hold water with less than 1500 kPa tension in at least 3 months of the growing season each year. Common moisture regimes are udic, ustic, or xeric. Often aquic conditions can be found. Udalfs are believed to be forested at least at some part of their development and are often intensively farmed.

Region 4 (AD-4)

In this region Ultic Tropudalfs are the dominating soil type. Tropudalfs have already been discussed above. Ultic refers to properties typical for an Ultisol.

Region 5 (AE-5)

In region 5 Vertic Tropudalfs are found. These soils have already been discussed above. The reasons this area was mapped separately mainly relies on the slope. This region is dominated by steeper slopes than those in region 3 (AE-4).

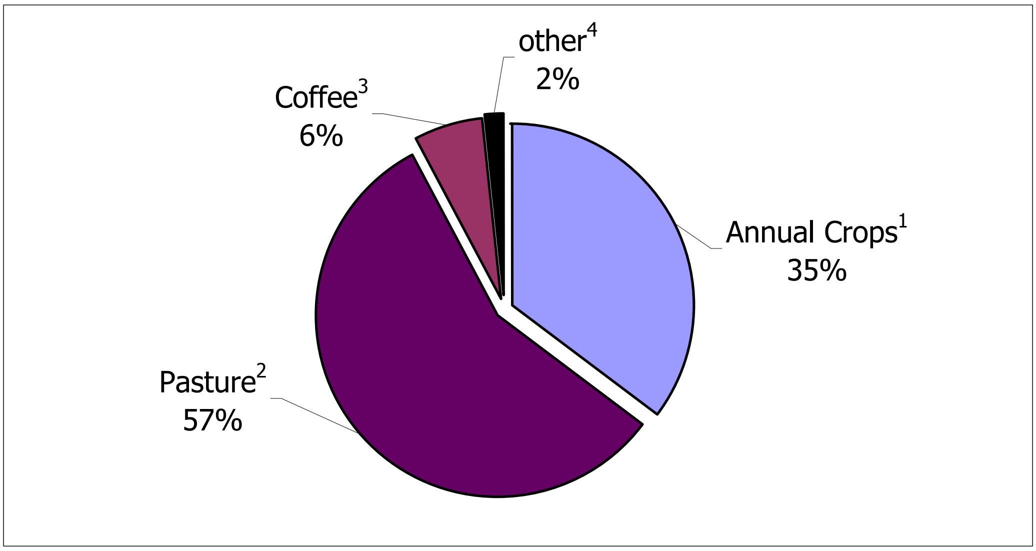
Region 6 (ME-5)

Region 6 (ME-5) is dominated by Vertic and Aquic Argiustolls. An Argiustoll is a Mollisol with ustic moisture regime that has an argillic horizon. Mollisols, aquic conditions and vertic properties have been discussed above. An argillic horizon is a subsurface horizon that has a significantly higher percentage of clay than is found in the overlying soil material. Evidence of clay illuviation is present. Argillic horizons may also be found at the surface in case the overlying horizons have been eroded.

2.1.4 Agriculture

A land-use map of 1996 gives a reasonable overview about the land use in the San Dionisio region during the event of Hurricane Mitch (MAGFOR, 1996b; Graph 3, p. 14). Pastures cover about 57 % of the San Dionisio region. Pastures are natural or improved and partly shrubby according to own observations (March 2002). Annual and perennial crop production is performed on about 41 % of the total area. Marketing of products is limited and subsistence agriculture is of major importance. The main crops cultivated are maize and beans. These are either intercropped or grown in sequence. Annual crops in total cover about 35 % of the study area. With about 6 % of the study area, coffee is the most important cash crop. Coffee is cultivated either shaded (banana, citric trees) or unshaded (MAGFOR, 1996b). Other forms of cash crop cultivation include sugar cane.

People perceive the lack of (potable) water for domestic and livestock consumption as the biggest problem in the dry season. The beginning of rainfall in April/May and its amount and distribution during the other months are of major importance during the rainy season.



[1] maize, beans, sugar cane; [2] natural pasture, improved pasture; [3] coffee, shaded & unshaded;
[4] settlements, forest, shrubland

Source: MAGFOR, 1996b. Modified.

Graph 3: Agricultural land use pattern in the San Dionisio region recorded in 1996 by MAGFOR. The original map was created by photo-interpretation.

2.1.5 Available Data

Special emphasis was put on the use of generally available or easily obtainable data. This allows a reproduction of the results by other users without the need of special equipment, special training, or a time and resource consuming process of data generation. Most of the data have different origins, but unless stated otherwise, it was retrieved from the CIAT databank. The data is however available from the mentioned original sources and includes:

- A digital elevation model (DEM). The DEM was established from aerial photos taken in 1996. The photos are available from INETER („*Instituto Nicaragüense de Estudios Territoriales*“). The DEM was created at CIAT. It covers the entire study area at a scale of 1 : 40,000 with a resolution of 15 m. A new DEM from more recent photos obtained from INETER during a visit in March 2002 is currently produced but was not yet available for this study.

- River coverage. A map showing the rivers in the study area at a scale of 1 : 50,000. The source is INETER (n.d.). Unfortunately, no documentation about the year the data was released is available. Originally a vector-file, the map was converted into a raster-file with a resolution of 5 m.
- Road coverage. Road data was available at 1 : 50,000 scale. The source of this map is INETER (1987). This map too was converted from a vector-file into a raster-file at a resolution of 5 m.
- A climate map. A map showing rainfall and temperature patterns in the study area at a scale of 1 : 50,000. The source is MAGFOR („*Ministerio Agropecuario y Forestal*“, Nicaragua, n.d.). Unfortunately, no documentation about the year the data was released is available.
- A land use map. The map was established by photo-interpretation by MAGFOR (1996b) using aerial photography from 1996. The scale is 1 : 50,000.
- Soil maps. Two soils map were available, both in the USDA (United States Department of Agriculture) classification system. The first map represents the entire study area at a scale of 1 : 500,000 (MAG, 1978), the second map covers only part of the study area at a scale of 1 : 50,000 (MAGFOR, 1996a). Digitalization of the maps was done at CIAT.
- Landslide point file. The landslide points were taken in a five week field-survey with a high precision GPS. Method and principles are described in chapter 2.2.1. A total of 144 landslides were identified with 165 points. Landslides that seemed to be significantly wider or longer than others were referenced with two points. As the models rely on point information of landslides, these points were later merged to a single point in a visual analysis using the contour lines as decision aid. Some landslides were located outside the study area and excluded which eventually resulted in a total of 121 landslides for further analysis.

2.2 The Field Sampling

Great care was taken to record the largest possible number of landslides with best possible precision. In total, 5 weeks were allocated and used for the travel to the region as well as the locating and recording of landslides. Further aid was available from CIAT personnel of the area and from a post-Mitch risk study on the area (LUNAS, 2001). This information helped to efficiently allocate the available time.

2.2.1 Georeferencing and Equipment

Georeferencing refers to determining the exact location of a point on the earth's surface. The coordinate system with which this location can be identified is known as georeference system (BONHAM-CARTER, 1994). Georeferencing of the landslide points was done with two „Leica Wild 200" high-precision Global Positioning System (GPS) units (LEICA GEOSYSTEMS, Heerbrugg, Switzerland).

To obtain a best possible precision, differential correction was applied. Using a high-quality differential GPS with post-processing of data would be sufficient to determine the positional accuracy of a 1 : 24,000-scale map (TEYTAUD, 1996).

Global Positioning System (GPS)

The GPS is operated by the United States (US) Department of Defense (DoD). DANA (1994) gives an overview of the GPS. Originally designed for the US military, the systems standard positioning services (SPS) are readily available to civil users worldwide at no charge. GPS provides specially coded satellite signals that enable a GPS unit to compute position, velocity, and time. A minimum of four so-called SVs (space or satellite vehicles) is required to compute positions in all three dimensions (latitude, longitude, elevation). GPS coordinates are based on the geodetic datum WGS-84. The WGS-84 reference system was developed by the US DoD to support satellite based global activities including mapping, charting, positioning, and navigation (SNAY & SOLER, 2000). A total of 24 SVs is active in orbit at all times since full operational capability was reached in April 1995 (USNO, 2002).

Accuracy is amongst the most frequent limitations in the application of GPS. Accuracy is affected by various factors. DANA (1994) discusses and explains these factors. The ones most applicable for this study are compiled and briefly explained in the following list:

- SV clock errors;
- Tropospheric delays, due to changes in temperature, pressure, and humidity associated with weather changes;
- Ionosphere delays due to ionized air;

- Multipath, caused by signals reflected from surfaces near the receiver;
- User mistakes, including incorrect geodetic datum selection;
- Receiver errors, such as software or hardware failures;
- Geometric Dilution of Precision (GDOP) and visibility, depending on the geometric relationships between the receiver position and the positions of the satellites the receiver is using for navigation.

Differential GPS (DGPS)

In order to minimize the GPS errors and to obtain a maximum possible precision, a differential correction was applied (TEYTAUD, 1996; CORVALLIS MICROTECHNOLOGIES INC., 2000). DANA (1994) discusses the basics of DGPS (Differential GPS). Generally in differential correction, bias errors at one location are corrected with measured bias errors at a known position. These are computed for each satellite signal by a base station used as a reference receiver. Limitations exist in the elimination of errors resulting from Ionospheric delays and Multipath (CORVALLIS MICROTECHNOLOGIES INC., 2000). The remote receiver (rover) and the base station have to be within a distance of 30 kilometers of each other (DANA, 1994). Correction is generally done with special software in a post-processing step. More recent systems also allow real time („on the fly“) processing.

2.2.2 Sampling Design

Systematic and exhaustive landslide detection and recording was done within the watershed's administrative sub-boundaries (ESPINOZA & VERNOOY, 1998). One to two of these sub-regions were covered per day, depending on their size and accessibility.

The base station was set up at the communal coffee drying and processing facility („*beneficiadero*“) of San Dionisio. Located in a fenced and secured environment about 200 m south of the local CIAT office, this location guaranteed recording without secondary disturbance, such as human or animal caused misplacement. The same GPS unit served as a base station during the entire study. In the field, about 40 to 50 measurements were taken in a 10 second interval per landslide point recorded. All geographic information was recorded in the WGS-84 reference system. Daily backups as well as processing and verification were performed to detect possible sampling errors. Differential post-processing was done with SKI 2.3 (Static Kinematic Software, ver. 2.3; LEICA GEOSYSTEMS, Heerbrugg, Switzerland).

In order to allow later cross checks with information derived from maps and to aid the spatial modeling process, additional site-specific information was collected:

- Photos, where possible and appropriate, using a single-lens reflex camera (Canon EOS Rebel 2000) and color print films for easy handling (Kodak Color, 200 ASA);
- Information on slope, estimated, as described in the Australian Soil and Land Survey Field Book (MCDONALD *et al.*, 1990), simplified;
- Degree slope, measured with a standard handheld clinometer;
- Vegetation density and type, estimated, as recommended by MCDONALD *et al.* (1990);
- Current land-use;
- Rock outcrop in the area, estimated as recommended in the USDA Field Book for Describing and Sampling Soils (SCHOENEBERGER *et al.*, 1998);
- Basic soils data according to the „*Bodenkundliche Kartieranleitung*" (AG BODEN, 1996) and the USDA Field Book for Describing and Sampling Soils (SCHOENEBERGER *et al.*, 1998), including:
  - Finger texture, simplified following WHITE *et al.* (1997);
  - Munsell moist color (MUNSELL, 1971); and
  - Percent (%) gravel estimate.

Not all data could be taken at all sites due to difficult terrain conditions, vegetation conditions or other constraints. Soils data were taken at a soil-depth of approx. 5 cm (in the „A" horizon) at the closest undisturbed point to the measurement location.

2.3 The Analysis

2.3.1 ArcView and Extensions

Principles and Description

ArcView GIS is a popular GIS platform from Environmental Science Research Institutes Inc. (ESRI) to „visualize, explore, query, and analyze data geographically" (ESRI, 1996a). It can access and handle data in various file formats. ArcView also was the platform of choice for the selected models, SINMAP and ArcWofE. The ArcView version used was ArcView 3.2.

ArcView capabilities can be greatly enhanced by so-called extensions. Extensions are available from various sources, including ESRI itself underlining the modular concept of ArcView. This helps to design ArcView to meet the needs of each user without the need to purchase or install unnecessary components. A popular platform to search and exchange these extensions is the Homepage operated by ESRI, „http://arcscripts.esri.com/“.

The following extensions were used:

- Spatial Analyst 1.1. This extension from ESRI is necessary to handle files in raster format (ESRI, 1996b). It is a requirement for SINMAP and ArcWofE. Spatial Analyst has to be purchased.
- Grid Analyst 1.1. Grid Analyst is a free ArcView extension developed by A. Saraf from the Department of Earth Sciences, University of Roorkee, India (SARAF, 2000). Grid Analyst offers a great variability of possibilities to manipulate or extract data from ArcView grid-files including statistics calculation.
- Table Select Deluxe Tools, developed by Soeren Alsleben (ALSLEBEN, 2001). It compiles various possibilities on how to select records from tables and was chosen to randomly select landslide points for the analysis with SINMAP.

2.3.2 Stability Index Mapping (SINMAP)

Principles and Description

SINMAP (Stability INdex MAPping; PACK *et al.*, 1998a) is a grid-based terrain stability predictive tool designed as an ArcView extension. This way ArcView's standard GIS functionality can be used for data input, data organization, data output, and presentation. The latest version released (1998) uses ArcView 3.0a for Windows or higher with the ArcView Spatial Analyst extension 1.0a. SINMAP can be applied in almost any region, but the underlying theory is restricted to shallow, translational landslides (PACK *et al.*, 1998a & 1998b).

The SINMAP program is available as public domain software on the Internet. Free downloads are possible, either from Utah State University at „http://www.engineering.usu.edu/dtarb/“, or from Terratech Consulting Ltd. at „http://www.tclbc.com/“. The homepage of Terratech Consulting could however not be accessed during the study.

The theory behind SINMAP is explained in detail in the SINMAP User's Manual (PACK *et al.*, 1998a) that is included in the download-package. Mathematical backgrounds are discussed in the manual's appendix. The source code is available to allow further development or adaptation to different operation systems or GIS platforms. Essential information is given below.

Theory

PACK *et al.* (1998a) state that the theoretical basis of SINMAP is the infinite plane slope stability model coupled with a steady-state topographic hydrologic model as pioneered by MONTGOMERY & DIETRICH (1994). The term 'steady-state' at this point does not refer to any long term, e.g. annual, averages, but to a critical period (event) of wet weather that is likely to trigger landslides. According to PACK *et al.* (1998a), an important difference to MONTGOMERY & DIETRICH (1994) is that cohesion is retained in the infinite slope stability model. Soil cohesion or root strength can be accounted for. Topographic variables are automatically computed from a DEM.

Important assumptions underlying the SINMAP theory include that the subsurface hydrologic boundary parallels the surface, and that soil thickness and hydraulic conductivity are uniform. Soil thickness is interpreted perpendicular to the slope. Edge effects are neglected. A dimensionless cohesion factor is established, combining cohesion due to soil and root properties and soil density and thickness. The resulting factor gives a ratio of the cohesive strength of the soil relative to its weight. Uniform probability distributions with upper and lower bounds of parameters account for parameter uncertainty (PACK *et al.,* 1998a).

The software includes an interactive visual calibration tool. Parameters can be adjusted referring to observed landslides, a specific catchment area, and to the stability index map. A slope plot with lines distinguishing the different stability classes and a table giving summary statistics are simultaneously available for decision support. This process can be understood as 'fine-tuning', with the result that the stability index map „captures" a high proportion of observed landslides in regions with low stability indexes.

Input and Output

Input can be classified into two categories, a combination of map coverage of the study area and calibration parameter values. The map coverage required consists of three different maps.

The accuracy of the output relies heavily on the quality of the DEM (PACK *et al.*, 1998a). Depending on the areal extent of the study area, its heterogeneity, or the information available, a decision between a single calibration region and a multi calibration region theme has to be made. Calibration regions are sub-samples of the total area of analyses in which selected properties are assumed to be uniform enough for further analysis (PACK *et al.*, 1998a). A single calibration region theme can be extracted from the DEM using the area coverage. A multi calibration region theme needs an underlying map showing regional patterns within the study area that meet the mentioned criteria. The third input map is a point map with locations of the sampled landslides. As SINMAP's concept is based on field information for calibration, the models output depends heavily on accurate positioning of known landslide initiation zones (PACK *et al.*, 1998a & 1998b). An important limitation of SINMAP is that all maps have to cover the same area.

Once the study area and the calibration regions are defined, the calibration parameters have to be quantified. Parameters to be specified are:

- The ratio recharge/transmissivity (R/T ratio);
- A dimensionless cohesion factor (C); and
- Soil friction angle (phi).

The R/T ratio is a soil parameter quantifying the ratio recharge (R = amount of water infiltration into the soil) over transmissivity (T = water flow within the soil). According to PACK *et al.* (1998a) the R/T ratio multiplied with the sine of the slope can be interpreted as the „length of the hillslope required to develop saturation“. The dimensionless factor for cohesion combines soil and root properties on the one hand, and soil density and thickness on the other. The angle of internal friction according to SATTERLUND & ADAMS (1992) equals to the angle of natural repose when loose soil particles are poured into a pile.

In a single calibration region theme, only one set of calibration parameters is required. For a multi region calibration theme, the parameters can be defined individually for each calibration region. As the corresponding assumptions of the program are mainly based on soil or soil-related properties, the 1 : 500,000 soil map (MAG, 1978) was used as an underlying parameter. This map has several advantages. Its scale maps out calibration regions reasonable in size and number. A map with a smaller scale or a combination with a second map, e.g. the land use map (MAGFOR, 1996b), would have yielded a high number of small calibration regions. This would have left calibration regions without landslide points that are necessary for calibration. SINMAP is explicitly considered to be used in combination with calibration data (PACK *et al.*, 1998a). The generation of calibration regions resulted in six calibration regions according to the six main soil types described by the map. Only one, very small, calibration region (region 2) located at the NE boundary of the watershed shows no landslide points.

The input parameters required by SINMAP have to be defined prior to an analysis. The values are entered in terms of upper and lower bounds. For the initial quantification of these values, two approaches are possible. The default values that are automatically set by SINMAP uniform for all calibration regions can be used as first input. These values are always identical, no matter to which study the model will be applied. The calibration process can then be used to adjust the values and achieve the best possible result. Within the calibration process, all values can be adjusted separately by calibration region. In a second way, user defined values can be entered for each calibration region. The same calibration process can then be used to fine-tune these values. Theoretically, both ways should end with the same values for each parameter in each calibration region and thus the same results. However, the second way, using user-defined values, should be quicker and easier if experience and knowledge on the study area are available. The values should only need little adjustment because they already reflect the conditions to be simulated. For this reasons, the latter way was chosen for this analysis. Problematic was the issue on how to obtain these values to justify the input. The parameters as such are not only difficult to measure, but a measurement at this scale would also require huge planning efforts and extensive field surveys. In addition, no previous surveys exist where these values could be taken from, neither can they generally be expected to exist. It has to be assumed that this issue may pose difficulties to many users who will thus refer to the default settings. One analysis with the default values will be done to compare the results.

As the use of measured values is not possible, the initial values for this study were estimated based on knowledge about the calibration regions, in particular about the landscape and the soil. The information gathered during the field survey added site-specific information. The values were then modified when necessary, according to the SINMAP calibration procedure. This procedure includes an interactive visual calibration, allowing to adjust parameters while directly referring to observed landslides. Utilizing the landslide points, this can be considered the linkage between the theoretical model and the fieldwork (PACK *et al.*, 1998a).

Some general considerations underlie the estimations:

- Soil water saturation is achieved. The R/T ratio was estimated considering the conditions necessary to achieve saturation in each calibration region.
- Cohesion is related to clay content and vegetation. Clays show great cohesive strength when below the plastic limit. Problematic for a proper estimation is that increasing water content can reduce granular friction in extreme cases to near zero and even cause sudden liquification (SATTERLUND & ADAMS, 1992). They also mention that it is generally agreed that live roots add to soil strength.
- The angle of internal friction depends on soil texture and structure. SATTERLUND & ADAMS (1992) report that the angle of internal friction of most soils lies between 30 ° to 45 ° with a mean of about 35 °, while loose, clayey soils can have friction angles of only a few degrees when saturated. Important factors determining the angle of internal friction mentioned are particle shape, mineralogy, and density. As mentioned before, saturation is assumed.
- The model is applied to an extreme scenario, such as Hurricane Mitch. The interpretation of the values has to be accordingly.

Region 2 (EC-5) is excluded from the analysis, as no landslide points exist to verify the calibration and the area is very small. As calibration, analysis, and evaluation are based on individual calibration regions, excluding one region will not result in a bias. Simply, in the final map the information for this region cannot be interpreted. The values implemented as initial parameters are listed in Table 1 below.

Table 1: Initial settings for all parameters by calibration regions as used for the SINMAP modeling. Values are estimates based on knowledge available for the calibration regions.

Region		**R/T Ratio**		**Cohesion**		**Friction Angle**	
# [1]	**code**	**lower**[2]	**upper**[2]	**lower**[2]	**upper**[2]	**lower**[2]	**upper**[2]
1	MH-4	200	500	0	0.12	15	20
2	EC-5	default	default	default	default	default	default
3	AE-4	200	500	0	0.15	13	20
4	AD-4	100	300	0	0.10	20	30
5	AE-5	300	600	0	0.25	10	15
6	ME-5	200	500	0	0.20	15	20

[1] number; [2] lower and upper threshold

The output most valuable for landslide risk assessment is a stability index (SI) map with an individual stability value for each grid cell. This value should not be interpreted as numerically precise but in terms of relative hazard. Generally, an SI value is a computed value defining the stability of a site. Values above 1 represent stability hereby. SINMAP calculates these values for the parameter range, starting with a „worst case scenario“, values representing the most unstable situation. Where the result models stability, the point is considered unconditionally stable. Second a „best case scenario“ is simulated. If the result model instability, the point is considered unconditionally unstable. For all other cases, the parameter range is included into the calculation and thus the final value does not represent an absolute term.

The SI is the probability that a location is stable assuming a uniform distribution of parameters. SINMAP differentiates between six different classes, representing ranges of the calculated SI's. Three classes account for locations where the SI's are larger than 1. „Stable“ refers hereby to locations with SI's of above 1.5, followed by „moderately-stable“ where 1.25 > SI > 1.5, and „quasi-stable“ with 1 > SI > 1.25. For all these classes, the parameter range cannot model instability. Three more classes represent the SI's below 1. „Lower-threshold“ summarizes 1 > SI 0.5, „upper-threshold“ 0.5 > SI 0. Here, the optimistic (upper-threshold) and pessimistic (lower-threshold) parameter range is required to model stability. Areas where the parameter range cannot model stability and thus 0 > SI, are classified as „defended“. SINMAP links the results to the forces necessary to create instability. According to this, stable areas would require significant destabilizing forces to fail, moderately-stable areas moderate destabilizing forces and so on. Table 2 summarizes the SI classes including the explanations as defined in the SINMAP manual.

Table 2: Stability index definitions and explanations.

Condition	Class	Predicted State	Parameter Range	Possible Influence of Factors not Modeled
SI > 1.5	1	Stable	Range cannot model instability	Significant destabilizing factors required for instability
1.5 > SI > 1.25	2	Moderately stable	Range cannot model instability	Moderate destabilizing factors required for instability
1.25 > SI > 1.0	3	Quasi-stable	Range cannot model instability	Minor destabilizing factors required for instability
1.0 > SI > 0.5	4	Lower threshold	Pessimistic half of range req. f. instability	Destabilizing factors are not required for instability
0.5 > SI > 0	5	Upper threshold	Optimistic half of range req. f. stability	Stabilizing factors may be responsible for stability
0 > SI	6	Defended	Range cannot model stability	Stabilizing factors required for stability

Source: PACK *et al.*, 1998a.

Several other maps created by the program show the values needed by SINMAP for the analysis. They can also be used for calibration and illustration. The principles underlying each map are explained in the SINMAP manual (PACK *et al.*, 1998a). These maps are:

- A pit-filled DEM. Here, internally drained pits are removed from the original DEM. This is important for several assumptions used in SINMAP (PACK *et al.*, 1998a).
- Flow direction. Flow direction is computed following the D∞ method (multiple flow direction method) after TARBOTON (1997). Each cell shows a value representing the direction of water flow within the cell down the slope.
- A slope map. Slope for each grid cell is automatically computed by SINMAP. An important fact is that SINMAP does not use the common ESRI Spatial Analyst method but uses own algorithms. These are discussed in more detail in the SINMAP manual (PACK *et al.*, 1998a).
- Contributing or specific catchment area. The specific catchment area according to PACK *et al.* (1998a) is „equal to the upslope area draining to the cell per unit length of contour through which that area drains".
- Saturation. Displays relative topographic wetness.
- SA Plot. This plot gives a view of the study area in slope-area space. The plot is created by extracting data from the slope theme, the contributing area theme, and the landslide theme.
- A statistical summary table. This table is computed by SINMAP upon user request. It shows all statistical relations necessary to evaluate the SINMAP results: The six classes, the area and percentage of the region in each class, the number of landslides and the percentage of landslides per class as well as the landslide density per km^2.

2.3.3 Weights of Evidence (ArcWofE)

Principles and Description

ArcWofE (Weights of Evidence extension for ArcView; KEMP *et al.*, 1999) is a free ArcView with Spatial Analyst extension for weights of evidence mapping. The latest version as of March 2002 was released to the public in 1999. The documentation (manual) was edited in June 21, 1998. ArcWofE and its documentation are available for download at „http://ntserv.gis.nrcan.gc.ca/wofe/„ (March 2002).

ArcWofE is a quantitative method, combining evidence in support of a hypothesis. Originally developed for non-spatial application in medical diagnostics, the method has been adapted to GIS applications in the 1980s to map mineral potential (KEMP *et al.*, 1999, RAINES *et al.*, 2000). Although originally designed for this application, the model can be used for different types of spatial predictions when „the goal is to predict the probability of point occurrences" (KEMP *et al.*, 1999). In this analysis, various data sets (maps) are used to explore the role of different spatial information in landslide occurrence. Used spatial information will be weighted with known landslide occurrences.

ArcWofE is designed to operate with an adequate number of known (landslide) occurrences (training data). If no training points are available or if the user decides that the points are not representative of the conditions in the study area, the weighting can be based on expert judgment. This also allows to develop various scenarios and e.g. to reflect opinions from several experts and/or to compare those to the results from the statistical analysis (KEMP *et al.*, 1999; RAINES *et al.*, 2000).

Theory

The weights-of-evidence method is based on Bayes' Rule of Probability. Bayes' Rule of Probability and its spatial application is explained by BONHAM-CARTER (1994) and in the ArcWofE User Guide (KEMP *et al.*, 1999). The assumption is made that the prior probability to find a point (landslide) on a unit area of the study region is equal to the training point density. If evidential themes are added, the posterior probability will either increase or decrease. The prior probability is „updated" by the evidence from the evidential theme resulting in the posterior probability. The probabilities are transformed into logits, resulting in the loglinear form of Bayes' Rule. This allows a simple adding of the probabilities from the evidential themes. Conditional independence is assumed between the evidential themes (KEMP *et al.*, 1999). This assumption is usually never completely satisfied and leads to an overestimation of the posterior probabilities in absolute terms. The relative variations are however not much affected if the assumption is violated (RAINES *et al.*, 2000).

Evidential themes can be either binary maps or multi-class maps. Evidential themes are created by associating the information in the maps with the known points (landslides). They may have categorical values (e.g. like soil maps) or ordered values (e.g. like elevation). The weight values are easy to understand: Positive values indicate that more training points occur than would be expected by chance while negative values indicate the opposite. A value of zero indicates that no spatial correlation could be identified (KEMP *et al.*, 1999; RAINES *et al.*, 2000).

Input and Output

Four main steps are necessary to build a weights-of-evidence model and run an analysis (KEMP *et al.,* 1999):

1. Building a spatial database.
2. Extracting predictive evidence.
3. Calculate weights for each evidential theme.
4. Combine the evidential themes to predict the (landslide) hazard.

The spatial database has to be established before the model and its tools are applied. Steps 2 and 3 are a processing of the input data (spatial data base) to meet the requirements of ArcWofE. The model provides tools that help to create the evidential themes.

To build the spatial data base, two tasks have to be considered. One is the expected relation to landslides and the other is the availability. Some maps are available as themes, others have to be extracted or manipulated to serve as input theme. Other information of interest might not be readily available. With this background, the following themes were identified or created for the spatial database of ArcWofE:

- DEM related data. Using the 15 m DEM described in chapter 2.1.5 as underlying input, several floating point grid-files with 15 m resolution were established using standard ArcView procedures. These are:
  - Elevation coverage;
  - Slope angle coverage; and
  - Slope aspect coverage (aspect).
- A curvature theme was created with LandSerf (WOOD, 2002; chapter 2.3.4).
- Road and river coverage (chapter 2.1.5).
- A soil map 1 : 500,000 of the entire study area and a soil map 1 : 50,000 covering part of the study area (chapter 2.1.5).
- A land use map (1996) 1 : 50,000 covering the entire study area (chapter 2.1.5).

The output of the model is mentioned in step 4, a map showing probabilities of landslide hazards based on the combined evidence. Besides this map, statistical tables are created that allow identifying the quality of the result and the importance (contribution) of each evidential theme to the result. This allows reconsidering the input data and the model setup. In the case of missing but desired information, such as e.g. the curvature data, additional tools such as „LandSerf" (WOOD, 2002) were utilized to establish it.

2.3.4 LandSerf

Principles and Description

LandSerf is a tool that allows visualizing and performing analyses on elevation models of continuous surfaces. Unique is its ability to perform surface analysis over a range of scales (WOOD, 2002). LandSerf is developed by Jo Wood and offered free of charge by the City University London's Department of Information Science. LandSerf is subject to ongoing development. The version used was the latest release as of July 2002, LandSerf 1.8. The last modification on the documentation used was on April 20, 2002. The program can be downloaded at „http://www.soi.city.ac.uk/~jwo/landserf/landserf180/". LandSerf was chosen to compute curvature data at different scales. This data was required as an input parameter for the analysis with ArcWofE.

Input and Output

The input data was a DEM of the study area with a resolution of 15 m, as described in chapter 2.1.5. The map is in raster format and can be exported in an ASCII-file format with ArcView. The ASCII-file format is the common way to exchange data between ArcView and LandSerf (WOOD, 2002). Different settings of the analysis window (kernel) allow an analysis at any scale (WOOD, 2002). The window (or kernel) size is set by defining the number of cells along one side. Three different settings of 5, 15, and 25 cells were chosen. This equals to a window size of 25, 225, and 625 cells respectively. The computed maps were saved in ASCII-file format and later imported into ArcView.

2.3.5 Model Validation

Model validation is one of the main tasks of this study. After implementation of all data in the modeling process according to the requirements of the models, statistical tools will be used to determine the quality and usefulness of the results. Two questions are of critical issue: [1] The quality of the prediction, measured in number of landslides that fall into regions categorized as critical and [2] the utility value of the map for decision-makers, indicated by amount of area (total or relative) per class. Land use planning implications or project priority planning need reliable modeling results. Most important in this regard is the utility value that is determined by the applicability of the results. Utility value is not measured in terms of an absolute number, but must rather be seen relative to other results or to the purpose it was created for.

For the evaluation of the quality of the prediction, 40 % of the landslides were excluded from the modeling procedure and used for evaluation only. In SINMAP this was done randomly for each calibration region with the Table Select Deluxe Tools. The selection by calibration region was chosen to avoid a possible over- or under-representation of one or more calibration regions. ArcWofE provides a menu that allows select the landslides randomly.

Various analyses are considered. First, the prediction of all landslides is analyzed. Critical issue here is the number of landslides that are captured in regions predicted to show a high risk. The quality of the results can now be evaluated by:

- The relative number of landslides in critical regions (percentage) of [a] the landslide point included in the modeling and [b] the landslide points that were excluded.
- A comparison of the trend of the prediction for both landslide categories (training points & evaluation points). This allows defining the robustness and reproducibility of the results. In theory, the same results should appear, regardless which landslides were used for the model building.
- The amount of area per class. This is a critical issue concerning the utility value of the results (maps). An over-proportional amount of area classified as critical will result in good predictive results but is of limited use regarding the application for practical purposes, such as change of land use pattern. Differences in amount of correctly predicted landslides and amount of area classified as critical will reveal if given the circumstances a high proportion of the area really is at risk or if important factors have been neglected in the modeling process.

3 Preparation of the Evidential Themes for ArcWofE

The evidential themes are derived from the spatial data bases following the steps 2 and 3 as described in chapter 2.3.3. Predictive evidence has to be extracted before the weights for each evidential theme are calculated (PACK *et al.*, 1998a). For this purpose, the data in the individual input themes, or the classes of this data, are statistically related to the observed landslide points and weighted. Weights are calculated for a „unit area" setting. This unit, measured in square kilometers (km^2), is independent from the grid cell size and defines the area at which the calculations are based. The unit area is also called the „unit cell". A value of 0.1 km^2 is recommended by the program through the dialog in which the initial settings are defined. However, a setting of 1 km^2 is used in a mineral exploration study with map scale of 1 : 250,000 yielding reasonable results (AGTERBERG *et al.*, 1990). As no sufficient record and experience as on what to base the unit area is available, the decision is made to use both values and compare the results while creating the evidential themes. It is believed that this will help to adequately judge on critical issues during the preparation procedure. The final analysis (creating the response theme) will be conducted with the recommended settings of 0.1 km^2. The calculated weights are basically the probability to find a point on a given unit area in a given class. They are calculated twice, once for the presence of a point (W^+) and once for its absence (W^-). The distance between these two values is expressed in the contrast value (C, with $C = W^+ - W^-$). Positive values indicate a map unit expects more events than it would expect by chance, negative values fewer (BONHAM-CARTER *et al.*, 1989; AGTERBERG *et al.*, 1990; BONHAM-CARTER, 1991; RAINES *et al.*, 2000).

ArcWofE differs between maps with „free data" and maps with „ordered data". Free data refers to data with a categorical or nominal measurement scale (e.g. a soils map), while ordered data is considered to follow an ordered measurement scale (e.g. elevation). Maps with line features, e.g. rivers and roads, that do not underlie either measurement scale have to be pre-processed. BONHAM-CARTER (1991) describes how a spatial relationship between such features and point locations can be established. He suggests to create a new map, buffering the line features at successive distances. The result is a map with an ordered measurement scale where distance classes are ascending with increasing distance to the original line feature. Buffering can be done by various means in ArcView (ESRI, 1996a & 1996b), but also ArcWofE makes this feature available in its pull-down menu. The buffering can be carried out on any file type without further processing. The result is a map in grid format. Table 3 (p. 32) lists all input themes and the measurement scale they underlie. All themes with the same measurement scale were treated with the same procedure during the creation of the evidential themes. The evidential themes can either be binary or multi class maps, however the binary form is the ideal format for evidential themes. Maps with fewer classes show smaller variances and thus more robust results (PACK *et al.*, 1998a; RAINES *et al.*, 2000).

Table 3: The table lists all input themes and their measurement scale.

Theme	Measurement scale
Elevation	ordered
Slope[1]	ordered
Aspect[2]	free
Curvature	free
Road[3]	ordered
River[3]	ordered
Soil, 1 : 500,000	free
Soil, 1 : 50,000	free
Land use	free

[1] slope angle; [2] slope aspect;
[3] considering the distance buffers established

To compute the statistical evidence necessary to create the evidential themes, three different calculation pattern are available:

1. Categorical calculation;
2. Cumulative-ascending calculation; and
3. Cumulative-descending calculation.

The cumulative calculations (2, 3) are applied to ordered data. Here, the weights for an initial class are calculated, and then the following class is added. A new weight is calculated for the two combined classes together and so on. The initial class can either be the lowest class (ascending calculation pattern) or the highest (descending calculation pattern). A direct comparison between cumulative-ascending and cumulative-descending weighting showed that both lead to the same results when applied to the data in this study. Therefore, decisions have been based on the results of the cumulative-ascending calculation only. As mentioned, the contrast value (C) indicates a threshold between the classes. Basically, the highest absolute contrast value indicates the threshold class (BONHAM-CARTER *et al.*, 1988; PACK *et al.*, 1998a). RAINES *et al.* (2000) mention that in many cases the contrast curve is not simple. They link this to statistical noise and factors unrelated to physical processes. As possible solutions, more complex interpretations, allowing of multiple class evidential themes, or discarding of unacceptable evidential themes are suggested. BONHAM-CARTER (1994) suggests a more complex interpretation where the significance of contrast values is verified with the help of the Studentized contrast value (stud(C)). The Studentized contrast value is the ratio contrast (C) over variance of contrast (σ(C)), thus stud(C) = C/σ(C). With it, the hypothesis C = 0 is tested. C = 0 would suggest that the process generating the map unit can be considered independent from the process generating the points. For absolute values of 1.96 and above, this hypothesis can be rejected with $\alpha = 0.05$ (BONHAM-CARTER *et al.*, 1989; AGTERBERG *et al.*, 1990; BONHAM-CARTER, 1991; RAINES *et al.*, 2000). Still, the threshold value is also subject to subjective judging. What „α“ can still be tolerated? Besides the above-mentioned criteria, BONHAM-CARTER (1994) states that „ideally it is nice to see a Studentized value larger than 1.5 or better 2“, allowing expert reconsideration of the resulting map and its sense. Creating an evidential theme from an input map is called generalization. PACK *et al.* (1998a) explain that generalization can be considered similar to the common reclassification procedures described for ArcView (ESRI, 1996a & 1996b). The advantage of the tools provided in the pull-down menu of ArcWofE is that it allows a direct interaction with the statistical evidence (tables) created by the program beforehand. For the cumulative calculation, the threshold value is used to cut off all classes below including the class carrying the threshold value from the remaining classes above. The generalization tool conveniently adds the new classification as a new value to the existing map, rather than creating a new map.

The categorical calculation is applied to free data. Here, the maps' classes are weighted individually. Due to the nature of the data and the calculation, no threshold value can be determined as described for cumulative calculation. Rather, the Studentized contrast (stud(C)) is used to determine, whether a class shows a significant correlation to the point data or not. Then the decision is made to regroup the classes, in this study in three criteria:

1. Class 1, independent. No spatial correlation can be determined between the area in this class and the point files.
2. Class 2, fewer. I the area of this class, fewer point occurrences can be expected as should be by chance.
3. Class 3, more. In the area of this class, more point occurrences can be expected as compared to by chance.

Again, the generalization tool adds a new value carrying the new classification to the existing map.

The procedures explained above are applied to all theme-files from the spatial data base. The considerations to create evidential themes are summarized below.

Slope aspect

Aspect is based on degree, with 0° = 360° representing due North (N). As two opposite aspects, e.g. East and West, do not necessarily exclude each other, aspect is considered to be free data. Climatic features, e.g. rain and wind, often show spatially variable patterns in occurrence, such as two main directions. This can depend on temporal causes, e.g. daytime or season or can have global climatic reasons. Generally, as there is no experience considering the boundary line between too many and not enough classes, common sense must be applied while reclassifying a map. Considering the nature of the aspect and common susception of compass-directions, such as North (N) or North-East (NE), a reclassification of the map to four and eight classes respectively is undertaken. The details on these new classes are shown in Table 4. „No aspect" was also accounted for in an own class. This class however showed no results in any processing and is therefore not included in the graphs. It is considered to be spatially independent and added to the respective class in the generalization.

Table 4: [a] & [b]. Tables illustrate the reclassification of aspect into four and eight classes and the respective original values in degree (°).

[a] 4 classes

class	aspect	from	to
-1	NA[1]	-1	
1	N[2]	0°	45°
		315°	360°
2	E[3]	45°	135°
3	S[4]	135°	225°
4	W[5]	225°	315°

[1] no aspect; [2] North; [3] East; [4] South; [5] West.

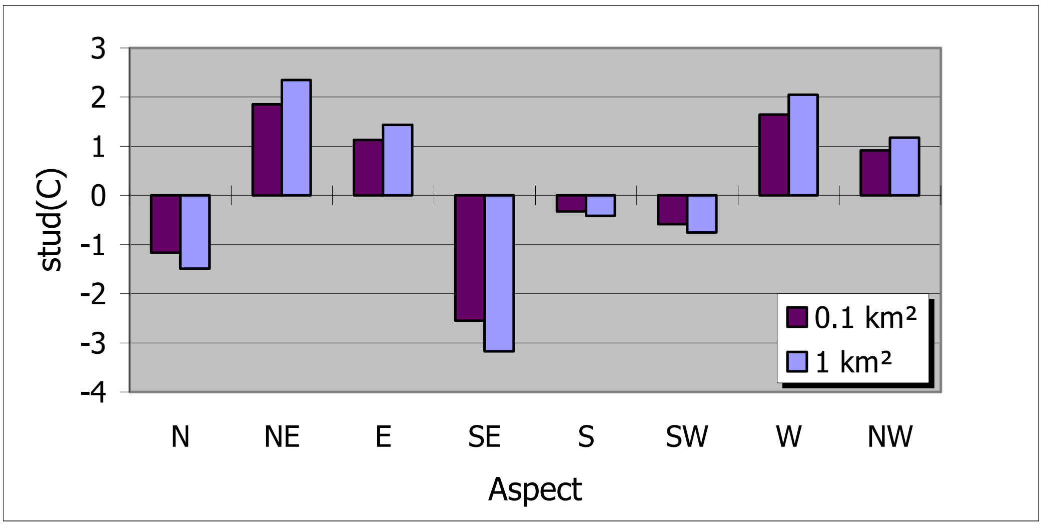
[b] 8 classes

class	aspect	from	to
-1	NA[1]	-1	
1	N[2]	0°	22.5°
		337.5°	360°
2	NE[2; 3]	22.5°	67.5°
3	E[3]	67.5°	112.5°
4	SE[4; 3]	112.5°	157.5°
5	S[4]	157.5°	202.5°
6	SW[4; 5]	202.5°	247.5°
7	W[5]	247.5°	292.5°
8	NW[2; 5]	292.5°	337.5°

For the 4-class aspect map, the due eastern region (E) showed a tendency to expect more landslide occurrences then it would expect by chance. The due southern (S) seems to expect less while the other classes show only little relation to landslide occurrence. The trend is similar for both unit-cell settings. As all values however are clearly below the significance, further analysis is concentrated on the map with eight classes and no evidential theme is created.

Graph 4 shows the Studentized contrast value from categorical calculation for aspect classified in eight classes. The unit area is set at 0.1 km² and 1 km². Clearly, the 'NE'-class shows a tendency to expect significantly more landslides than expected by chance. The due western class (W) shows a similar behavior but a rather low value (1.65) in the smaller unit area setting. In the 'SE'-class, fewer than expected events occur. The other classes can be considered independent. These results are within the trend of the 4-class map, e.g. Eastern classes being positive and southern being negative. The combination of classes yielding positive and negative values, e.g. NE, E and SE in the 8-class map approximately equals to E in the 4-class map, can explain the low values in the 4-class map. These results support the decision to continue with the 8-class map.

As subjective judging in interpreting the Studentized contrast value is necessary, the decision is made to create two evidential themes. One treating W as to expect more occurrences, and a second with W considered independent. The principle of the generalization is illustrated in Table 5. The two maps will be evaluated against each other keeping all other evidential themes constant and changing only the aspect value used. Questions to be answered include [a] is either map relevant for the calculation of the final result and if so [b] how does the result change when class 'W' is included.



Graph 4: Studentized contrast (stud(C)) for each class and two different unit area settings of 0.1 km² and 1 km² for aspect classified in eight classes.

Table 5: [a] & [b]. The tables show the new classes after generalization was undertaken and the criteria for the grouping of the old classes. Values 2 and 3 are added to the existing aspect map.

[a] value 2

new class	criteria	old class
1	independent	N, E, S, SW, W, NW, -1
2	fewer[1]	SE
3	more[2]	NE

[b] value 3

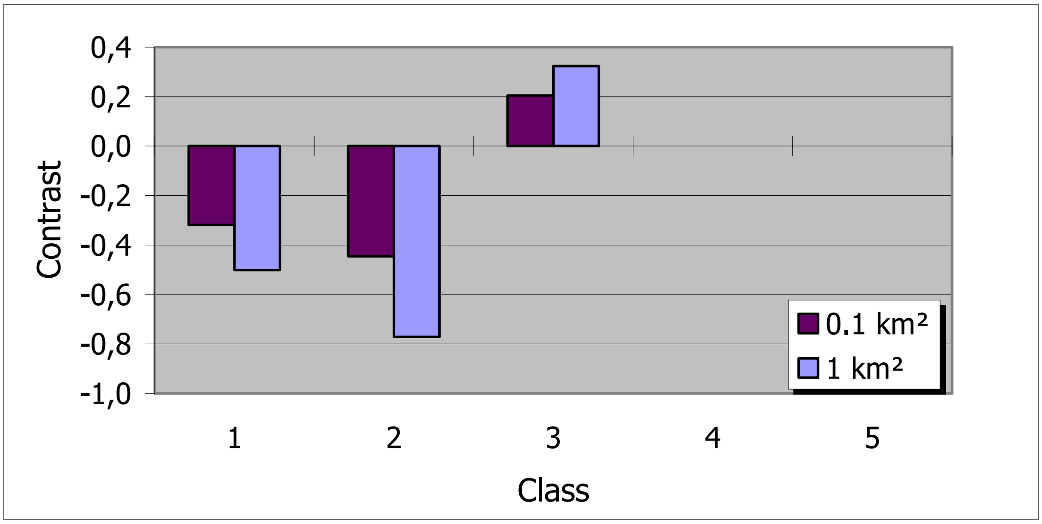
new class	criteria	old class
1	independent	N, E, S, SW, NW, -1
2	fewer[1]	SE
3	more[2]	NE, W

[1] fewer than expected by chance landslide occurrences observed; [2] more than expected by chance landslide occurrences observed

Elevation

As described in table 3, elevation is considered to follow an ordered measurement scale. In order to reduce the number of classes, the elevation theme was reclassified into five and ten classes, assigning approximately 200 m and 100 m per class. The results from cumulative ascending weighting for the map with five classes are illustrated in Graph 5. The highest contrast value, and thus the threshold, can be determined at class two. The map with ten classes is analyzed accordingly. The results for this map lead to a different conclusion. Class seven is identified with the threshold. However, the first seven classes of this map account for 94.5 % of the area and 72 out of 73 recorded landslide points. Also the Studentized contrast and therewith the significance is comparably low. This result can be interpreted in two ways. Either, no distinct relation between landslide occurrences and elevation exists in the study area, or the scale of the 10-class map is too broad to identify it. In the first case, elevation information should be omitted in the final calculation. In the second case the 5-class map can be processed and the 10-class map will be discarded.

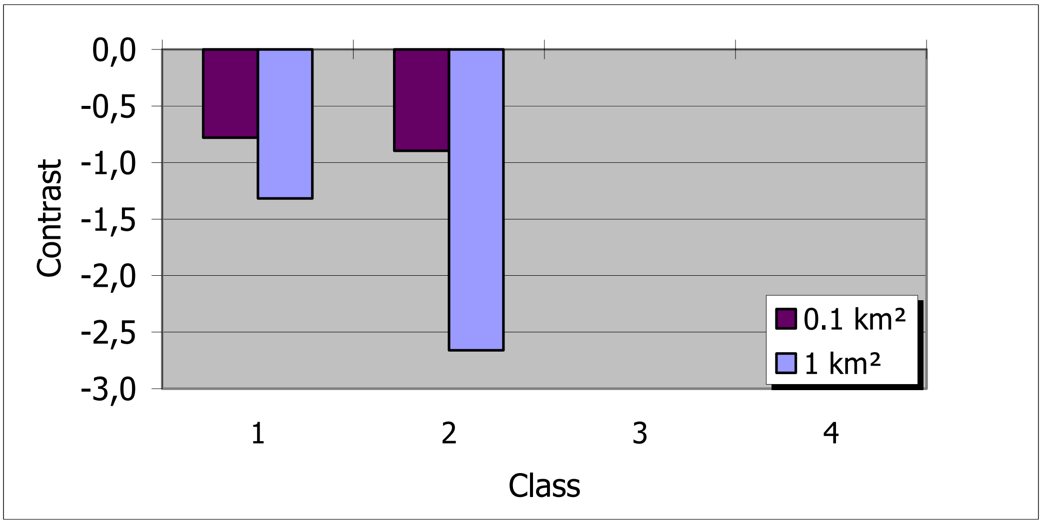
Considering the good results yielded from the 5-class map, this map is generalized and will be used as an evidential theme. For this purpose, class one and two are combined to a new class one and the remaining classes three, four, and five are combined to a new class two. This information is added as value 2 to the existing map.



Graph 5: Contrast values for elevation with five classes and cumulative-ascending calculation for two different settings of the unit area.

Slope angle

The slope theme is reclassified using 15 degree and 10 degree steps. By this way, two maps are created, with four and six classes respectively. The results of the cumulative-ascending based weighting for the slope-angle map classified in four classes are illustrated in Graph 6. Clearly, the threshold value appears in class 2. This assigns all slopes below 30° into a new class 1 and all above into a new second. The map with six classes shows less distinct results. Depending on which unit area setting is applied, the threshold classes are different within the calculation and also different as compared to the map with four classes. The higher setting of the unit-cell value (1 km²) however would support the results reported for the 4-class map. The other result with a unit area of 0.1 km², would assign all slopes below 40° to a new class. This would equal to 99.4 % of the area and 71 out of 73 landslide points and is thus not considered. The decision is made, to use the results from the map with four classes and generalize an evidential theme. The lower resolution with fewer classes seems to deliver the more stable results. Additionally, a second map is created where expert opinion about the slopes is considered. The majority of the landslides has been observed between 10° and 28°, this range will be classified in one class and all values below and above in a second. The resulting maps will be evaluated in the final calculation.

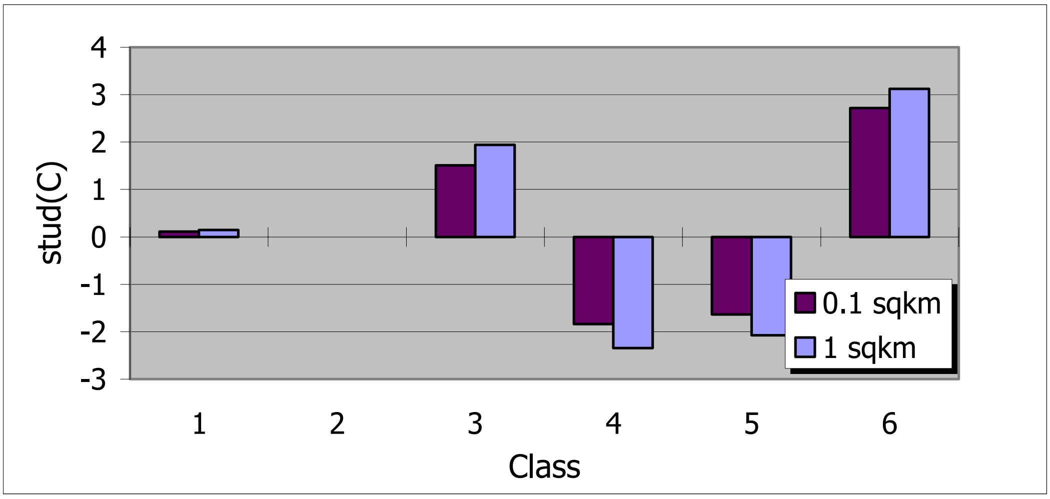


Graph 6: Contrast values by class for slope-angle classified in four classes. Contrast values are shown for two different settings of the unit area.

Soil

Different to SINMAP, ArcWofE allows to use themes with different extent of area. The area outside the defined study area is generally ignored, and the part of the study area that is not covered is marked as missing information. The area lacking information is then ignored in calculations with the respective evidential theme. This allows to utilize the information from both soil maps, including the soil map 1 : 50,000. In the processing, the soil maps will be converted into a raster based format (grid). This made it necessary, to decide on a grid-cell size. The decision was made, to choose the 15 m grid-cell size as also used in the DEM and all derived maps.

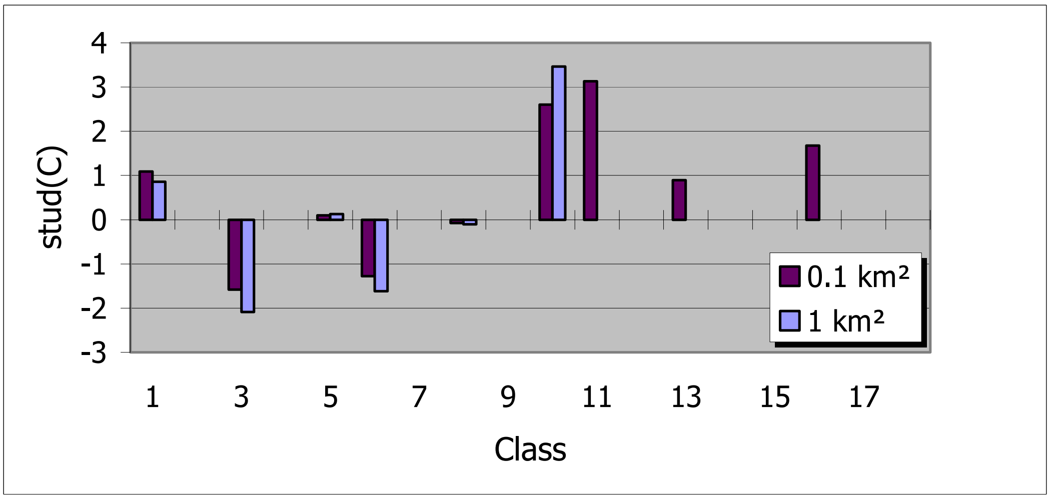
The 1 : 500,000 map comprises 6 classes. The categorical calculation is again done for the unit-cell settings of 0.1 km² and 1 km². As Graph 7 shows, the trend is similar for both calculations. Due to the clear results, easy generalization was possible. Classes 1 and 2 form the independent group, 3 and 6 show more and 4 and 5 fewer then expected landslides.



Graph 7: The graph shows the Studentized contrast (stud(C)) for each soil-class and two different unit area settings for the soil map at a scale of 1 : 500,000.

As can also be seen in Graph 8, the results from the 1 : 50,000 map are more difficult to interpret. While the calculations for the unit area setting of 1 km² show the same trend as compared to the calculations for 0.1 km², some of the classes remain without any value although the results in the calculations for a unit area of 0.1 km² have been very distinct. The best example for this is class eleven with a Studentized contrast value of 3.1 in the 0.1 km² calculation. This can be explained with the unit area size exceeding the class size.

The decision is made, to combine the results. Class 3 clearly seems to expect less landslides then it would by chance. The classes ten, eleven, and sixteen are grouped together and considered to expect more than average landslides. The remaining classes are considered independent.



Graph 8: The graph compares the Studentized contrast (Stud(C)) for each soil-class and two different unit area settings for the soil map at 1 : 50,000 scale.

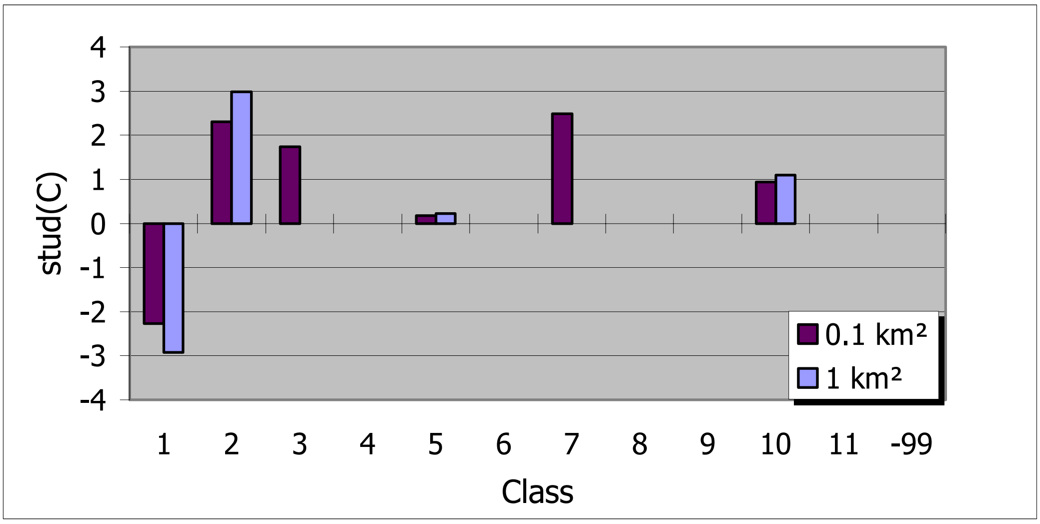
Land Use

Considerations regarding the classification system used in the original map from MAGFOR (1996b) and whether benefits could be expected from a reclassification were made. Pastures are e.g. classified in four different classes, annual crops in two. The decision was made, to create and evaluate two maps with different classification: One map equal to the original classification, showing eleven classes and a second map, where some classes are combined creating a map with less variation. The classification is illustrated in Table 6, with „class value" describing the original classification and „reclass value" showing the combination pattern. The original shape file was converted into a grid file with 15 m resolution.

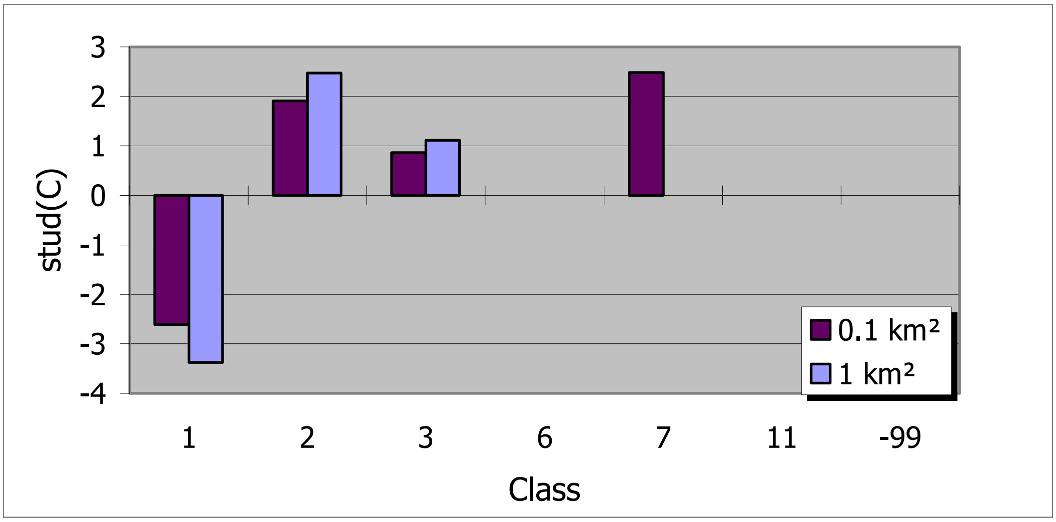
Table 6: Original classes and combination pattern of the land use map.

Class value	Description	Reclass value
1	Annual cropland, weedy	1
2	Pastures, weedy	2
3	Coffee, no shade	3
4	Annual cropland	1
5	Coffee, shaded	3
6	Urban areas	6
7	Forest	7
8	Pastures, minor cultivation	2
9	Pastures, shrubby	2
10	Pastures, improved	2
11	Shrubland	11
-99	No data	-99

The calculation results from both maps deliver reasonable results. As can be seen in Graph 9, some classes are not showing results at the unit area setting of 1 km². They are smaller than the unit area and thus support the decision to reclassify the map and generate larger classes. Generalization was done with classes 2, 3, and 7 considered to expect more then by chance landsides and class 1 to expect fewer. The other classes show no relation to landslide occurrence. The results from the calculations for the reclassified land use map are similar to the one done for the original classification and illustrated in Graph 10. Combined coffee (class 3) now stays below the threshold. In map 2, classes two and seven seem to expect more landslides and class one fewer. The remaining classes are again considered independent.



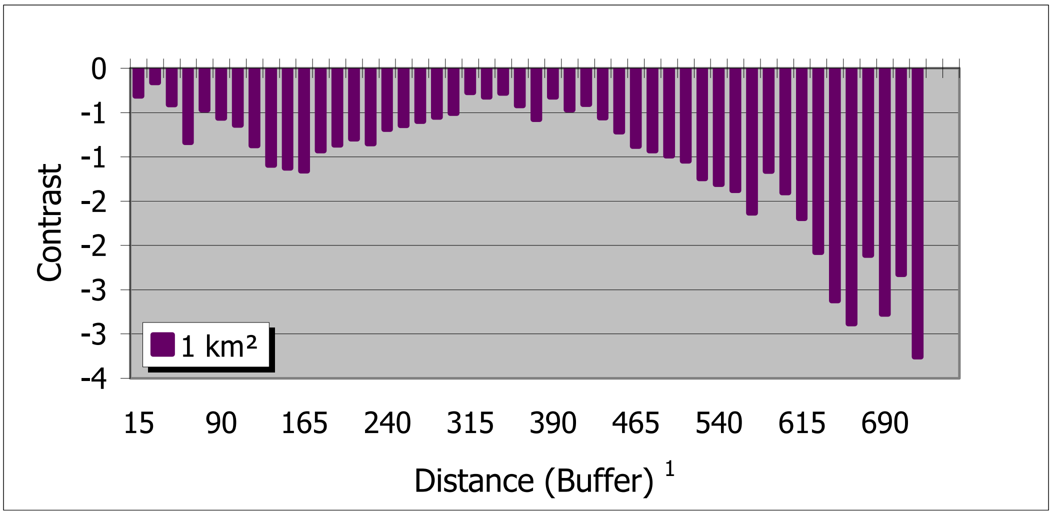
Graph 9: Land use, original classification. Studentized contrast (stud(C)) values for each class at two different settings of the unit area.



Graph 10: Land use reclassified. Studentized contrast (stud(C)) values for each class at two different settings of the unit area.

Rivers

As mentioned earlier in this chapter, buffer-zones will be established to identify a statistical correlation between the rivers, more precise the distance to the rivers, and the landslide points, following BONHAM-CARTER (1991). This is expected to lead to a binary map. The buffering procedure will yield a distance map in grid format. Considering the size of rivers and landslides, a 5 m grid-cell size and a 15 m buffer interval was chosen. An additional evaluation with different buffer-sizes between 5 m and 50 m showed no significantly different results in terms of what distance showed the respective threshold value. If so, this was linked to changes in the class-boundaries. With a unit area setting of 0.1 km², the threshold value is associated to the distance of 1005 m. As displayed in Graph 11, the results from the calculations for the area unit of 1 km² yield a lower threshold at 720 m. Both values also show a high Studentized contrast value. Looking at the possible results from the setting of the unit area of 0.1 km² revealed that 99.2 % of the area with 69 out of 73 landslide point would fall into one class. With a setting of 1 km², these values are 91.4 % with 59 out of 73 landslide points respectively. Due to this, the choice is made to generalize the map with the results from the 1 km² unit area based calculation.

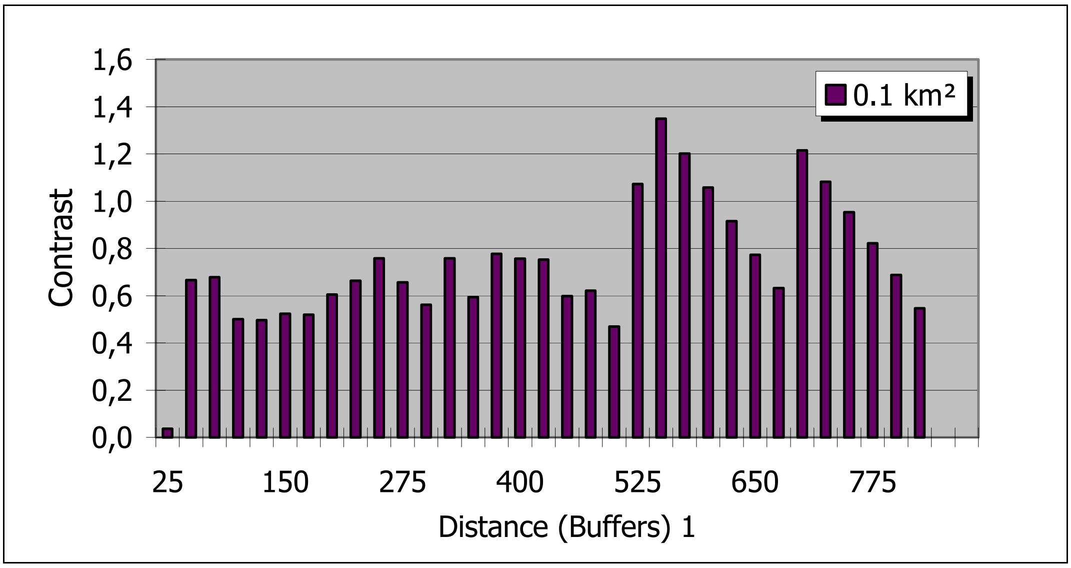


[1] For simplicity the x-axis ends at 735 m. Beyond, no values were showing.

Graph 11: Contrast value of successive distances to rivers calculated for a unit area of 1 km². The limitation to display 1 km² only is due to priority of the data and graphical limitations.

Roads

As the road coverage also is a line theme, the same processing steps apply as described for the rivers in the abstract '*Rivers*'. Identical values were used for the grid-cell size (5 m), but a buffer width of 25 m was chosen as a matter of convenience. The result from the weighting is identical in its trend for both setting of the unit area. It is illustrated for a setting of 0.1 km² in Graph 12 and identifies the buffer at 550 m as a threshold class. The map is generalized accordingly.



[1] For simplicity the x-axis ends at 875 m. Beyond, no values were appearing.

Graph 12: Contrast value of successive distances of 25 m to roads in the study area, calculated for a unit area of 0.1 km².

Curvature

Curvature coverage of the study area was created with LandSerf as described earlier. As mentioned, curvature was calculated at various scales and saved as individual files. These files were then again imported into ArcView and processed. Processing included the reduction of curvature classes from floating-point data to three classes: concave (1), no curvature (2), and convex (3). These classes were then weighted and evaluated for generalization.

The results showed a general tendency to expect more landslides on concave areas and fewer on the convex. This was identical at all scales. However, the observation for free data is based on the Studentized contrast value. As explained before, the magnitude of the Studentized contrast also indicates the significance of this observation. For curvature, all Studentized contrast values stayed below any level that would have suggested a significance. Curvature is therefore excluded from the analysis.

4 Results

4.1 The SINMAP Modeling

SI maps can stand alone and do not need much explanation besides the legend. A general advantage of maps is that results from different models or model parameter settings are visible and can be compared directly. Further, the maps and their attributes can be and are summarized in statistical tables. These help to assess the accuracy of prediction measured by the proportion of known landslides captured in areas associated with instability risks and the utility value considering the whole map. Additionally, SINMAP allows to look at these factors and to compare the results considering individual calibration regions.

4.1.1 The Calibration Process

The advantage of the calibration process in SINMAP is that improvements can be made for small areas. Good results of e.g. one calibration region can be improved or simply remain unchanged while other calibration regions with less satisfactory results can be modified. This especially helps to identify regions that show a different behavior and thus need more attention during calibration. This also helps to understand the relationship between individual parameters and the results.

A problem in SINMAP that appeared was that not the total region and the total number of landslides are accounted for in the SI map. In every analysis, some part of the region and some landslides showed no results (SI values). The error was however consistent: Always the same landslides and part of the area showed no results. Therefore the amount of area in total and the size of each calibration region were identical between the analyses. „Missing" landslides too appeared in all calibration regions. Reasons could not be identified, nor are any indications mentioned in the literature. Possible explanations include too high (> 10) or too low (< 0) SI values that are out of the range of calculation of SINMAP.

4.1.2 The Results

The total area SINMAP calculated results for is less than the known area of the study region, about 130 km^2. From the 72 landslide training records used as input, 55 yielded a result, and from the 49 landslide validation records, 43 showed a result. All further analysis and evaluation is tailored to these numbers. All percentages refer to these values as 100 %.

A general consideration in interpreting the results is that all SI below one (1) refer to conditions that are highly unstable and thus critical. They are usually accounted for in three classes. In the description below, the three underlying classes for both situations (SI > 1 and SI < 1) have been combined. Accordingly, summarized values are presented unless mentioned differently. The underlying idea is that all SI-values below one are a reasonable result. The splitting into several classes however helps in the calibration process and to understand and apply the map, e.g. to identify priority regions. It is part of the utility evaluation. A brief overview of the results is given in Table 7. The results are explained below in more detail.

Table 7: Summary of the results from SINMAP. Percent landslides captured are listed with percent area classified as critical.

Setting[1]	% Landslides[1]			% Area[2]	Ratio
	Input	Evaluation	Total		
expert	89	88	88	75	1.17
mod 1	78	79	78	65	1.2
mod 2	78	79	78	66	1.18
default	13	12	13	11	1.18

[1] with an SI < 1; [2] with an SI < 1

Expert values

Looking at the whole map (Figure 3), about 89 % of the landslides used in the analyses and about 86 % of the landslides held back for evaluation are located in areas with an SI of one (1) or below. This refers to approximately 88 % of all landslides captured in areas with low to very low SI (Table 7). About 75 % of the study area is classified with SIs below one. The ratio of captured landslides (total) and area classified as critical is 1.17. The map is illustrated in Figure 3 (SI map for expert settings, p. 49). Classes 5 and 6 as defined for SINMAP (compare Table 2, Stability index definitions, p. 24) have been combined in one class (SI 0 - 0.5).

The individual calibration regions contribute to this result in different ways. The calibration regions 3, 5, and 6 show similar results (data not provided) compared to each other and the mentioned mean of 75 % of the area classified as unstable or critical. In particular, SI's close to one (lower-threshold class, for class explanation compare Table 2, p. 24) show the largest share on the total area. This share decreases with decreasing SI's, the class with the lowest SI (zero) (defended) has the smallest share of area. The accuracy of prediction in these calibration regions is 90 % (calibration region 3) and 100 % (calibration regions 5 and 6). Regions number 1 and 4 show different patterns. In calibration region 1, about 84 % of the area are classified as unstable with about half of that predicted in the most critical class (defended) with an SI of zero. Accuracy of prediction is about 92 %. Region 4 (AD-4) maps about 54 % of the area with an SI below one. With a capture rate of about 71 %, this region is clearly below the overall average of prediction accuracy. Region 2 was excluded from the analysis.

Modification 1

Goals in the calibration are to either increase the proportion of landslides captured in regions with low SI, or to minimize the proportion of area classified with low SI without compromising much of the point prediction accuracy.

As a result of parameter adjustment, the amount of the area classified as critical with SIs below one (1) decreased to 65 % of the total study area (Table 7, p. 46). Although everything was done to sharpen the boundaries between the classes and obtain a higher precision with regard to the parameter settings, the accuracy of prediction also decreased. 78 % of the landslides used in the modeling were captured and about 79 % of the evaluation points. This equals to an overall prediction accuracy of about 78 %. The ratio between captured points and share of the area classified as critical is 1.2. The map is illustrated in Figure 4 (p. 50).

Looking at the calibration regions, regions 3, 5, and 6 remain very similar to each other and in general trend (data not provided). The amount of area classified as critical is close to the mentioned mean of 65 %, but prediction accuracy in region 3 decreased to 86 % and remained stable (100 %) in regions 5 and 6. Region 1 shows less variation than before, now 69 % of the area are classified as critical. Especially the proportion of area classified with an SI of zero was significantly reduced to 10 %. The prediction accuracy of region 1 dropped to 58 % of the input points, as compared to 92 % in the expert setting. Region 4 reaches this accuracy (about 57 %) with only about 48 % of the area classified as critical.

Modification 2

Trying to further fine-tune the parameters, the parameter settings were adjusted in modification two. As a result, prediction accuracy remained unchanged as compared to modification 1, with about 78 % of the input points and about 79 % of the verification points captured in areas classified as unstable. Overall area classified as critical increased slightly to 66 % of the study area (Table 7, p. 46). Also the values for the calibration regions did not change in absolute terms compared to as described in the abstract '*modification 1*'. The main difference showing is a shift of proportions within the area classified as unstable (data not provided). In modification 2, all calibration regions classified the largest share of the area considered unstable close to the critical value of 1 and the clearly lowest with an SI of zero. The map is shown in Figure 5 (p. 51).

Default settings

The default values differ quite a lot from the expert settings or their modifications as described above. Accordingly they represent an extreme change with regard to the parameters. It is expected that these values represent or are close to settings common for „normal" climate conditions. About 13 % of the landslides used in the modeling process and about 12 % of the verification points are captured in areas considered unstable. This numbers however show a high variation between the calibration regions. In region 4, about 43 % of the landslides are captured - on 8 % of the area. The same share of landslides is however also predicted in the most stable class of that calibration region. In region 5, 25 % of the landslides are predicted on 8 % of the area, while in region 6 no landslides have been captured, although about 12 % of the area is considered unstable (data not provided). Interesting is the result for region 1, where still about 20 % of the area is classified as unstable. Looking at the total area (Figure 6, p. 52), the share of the study area considered unstable is about 11 %. Interesting is also that no calibration region shows areas classified with an SI of zero.

Figure 3: SI map for expert settings.

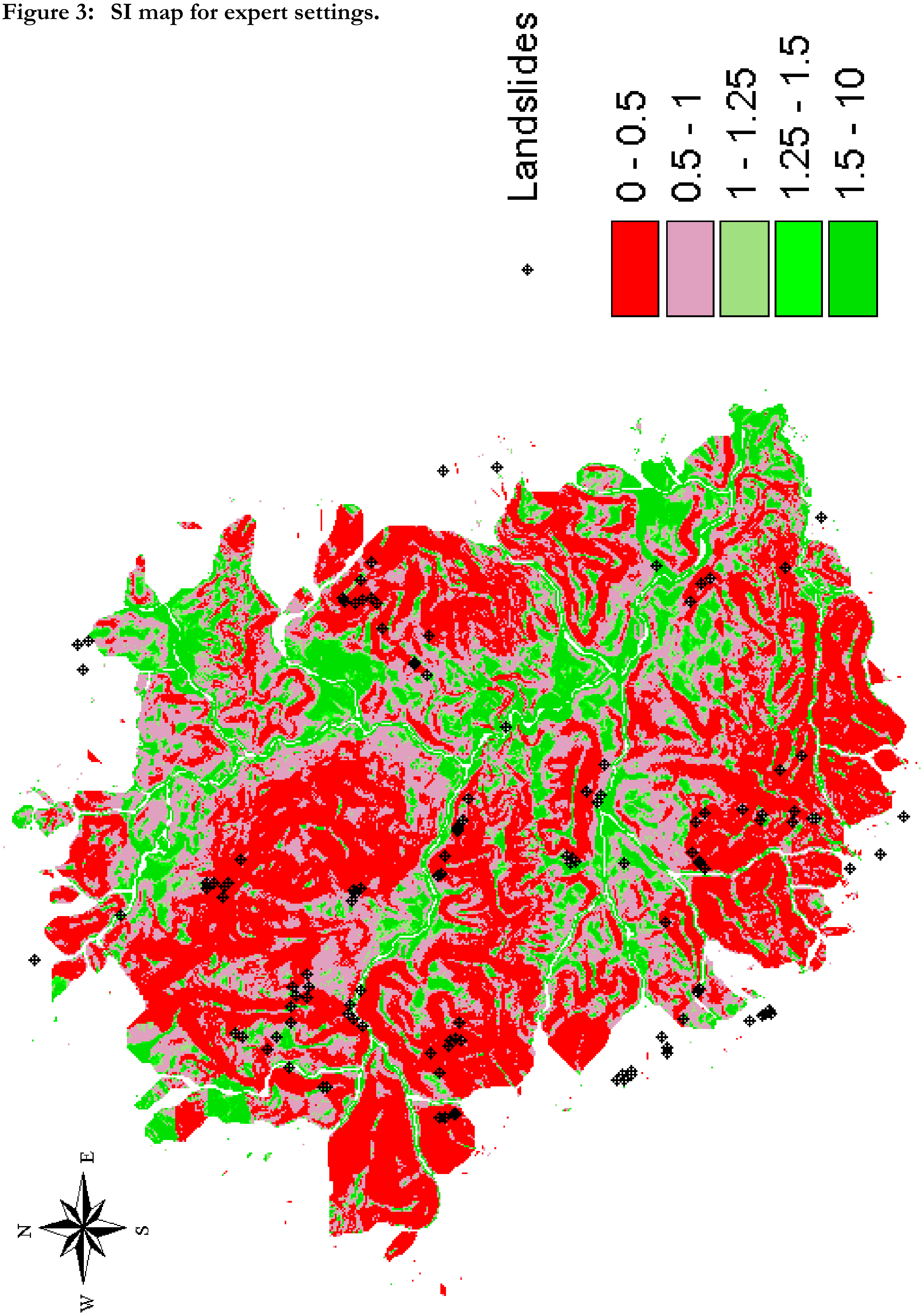


Figure 4: SI map for modification 1.

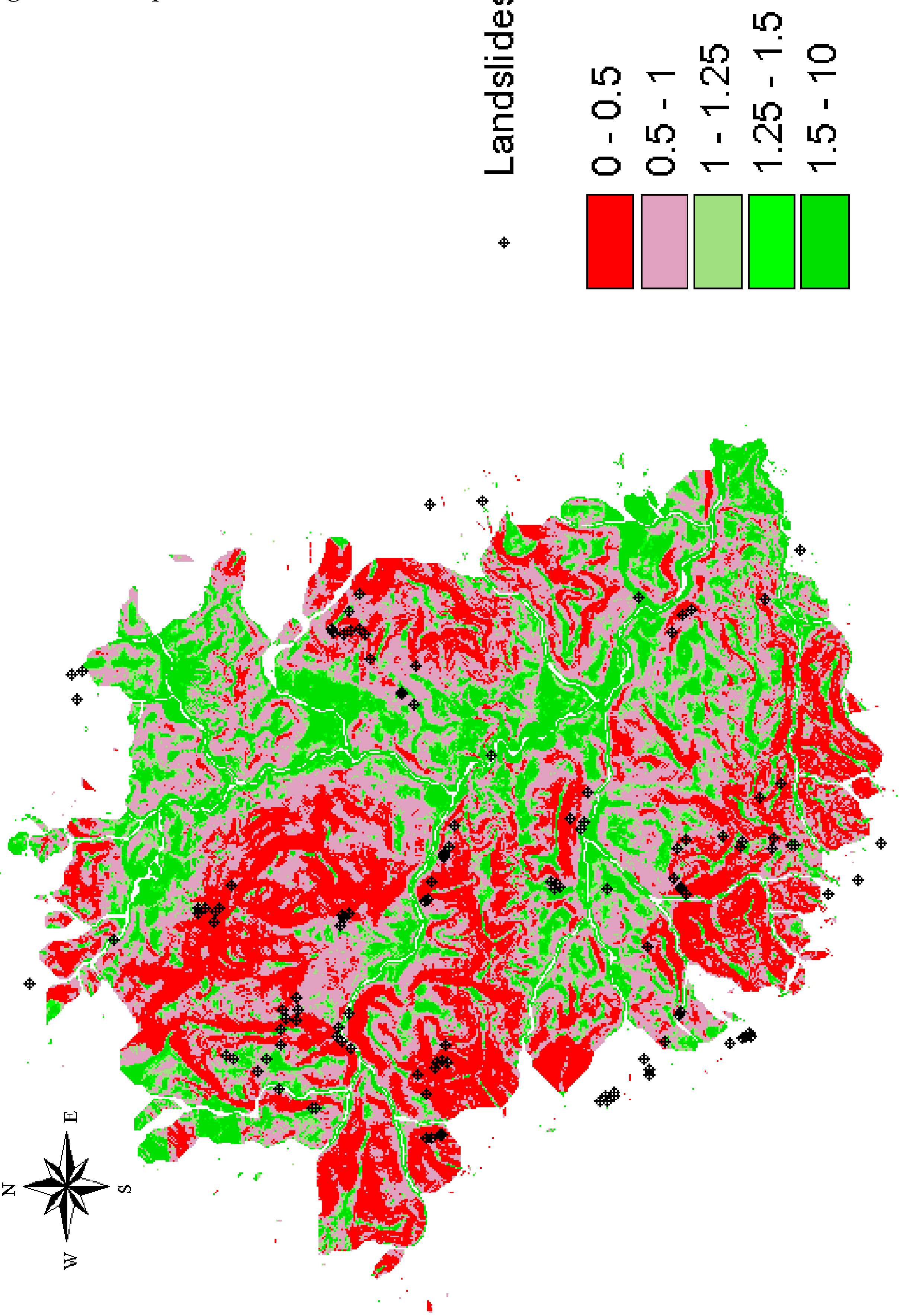


Figure 5: SI map for modification 2.

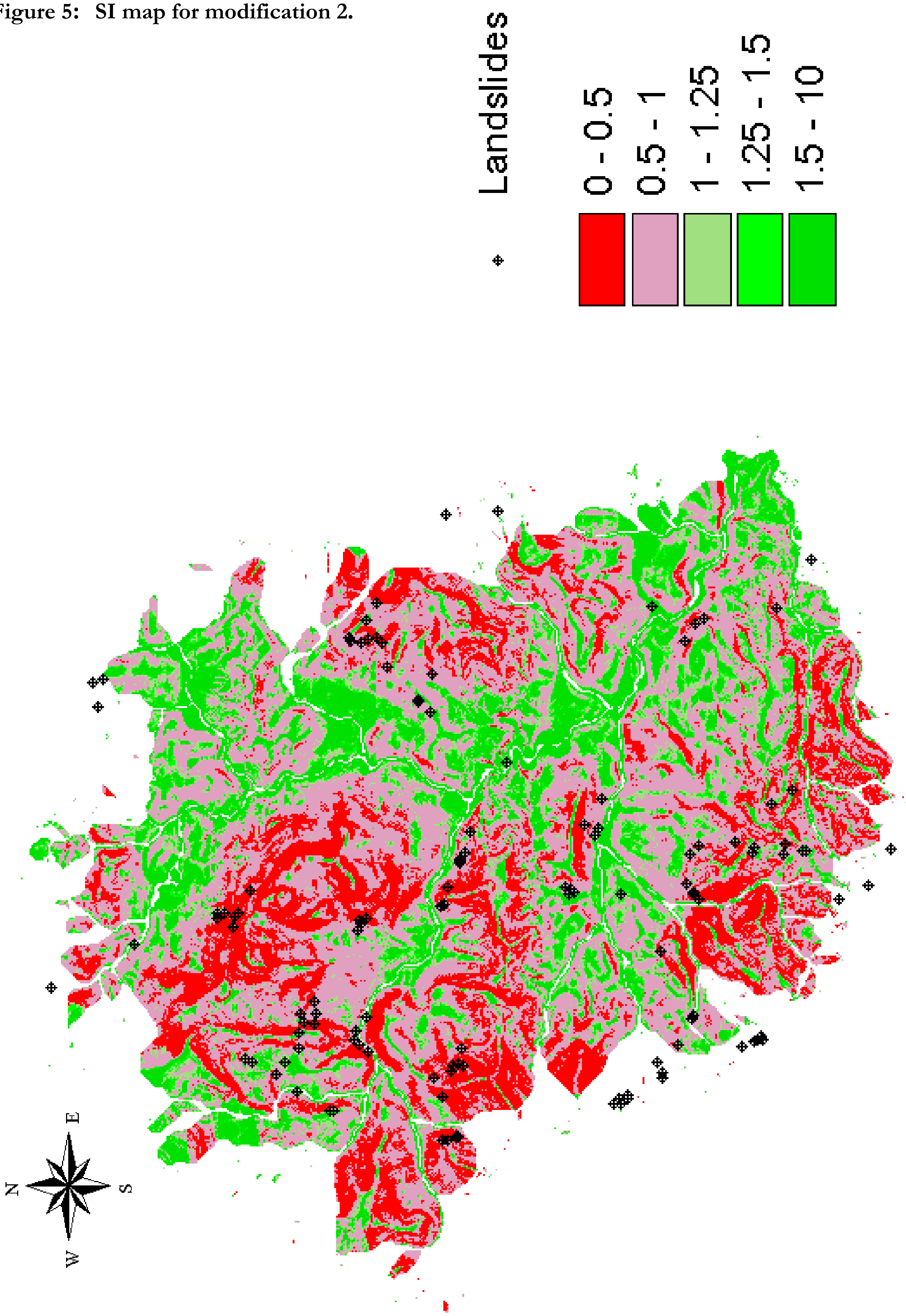
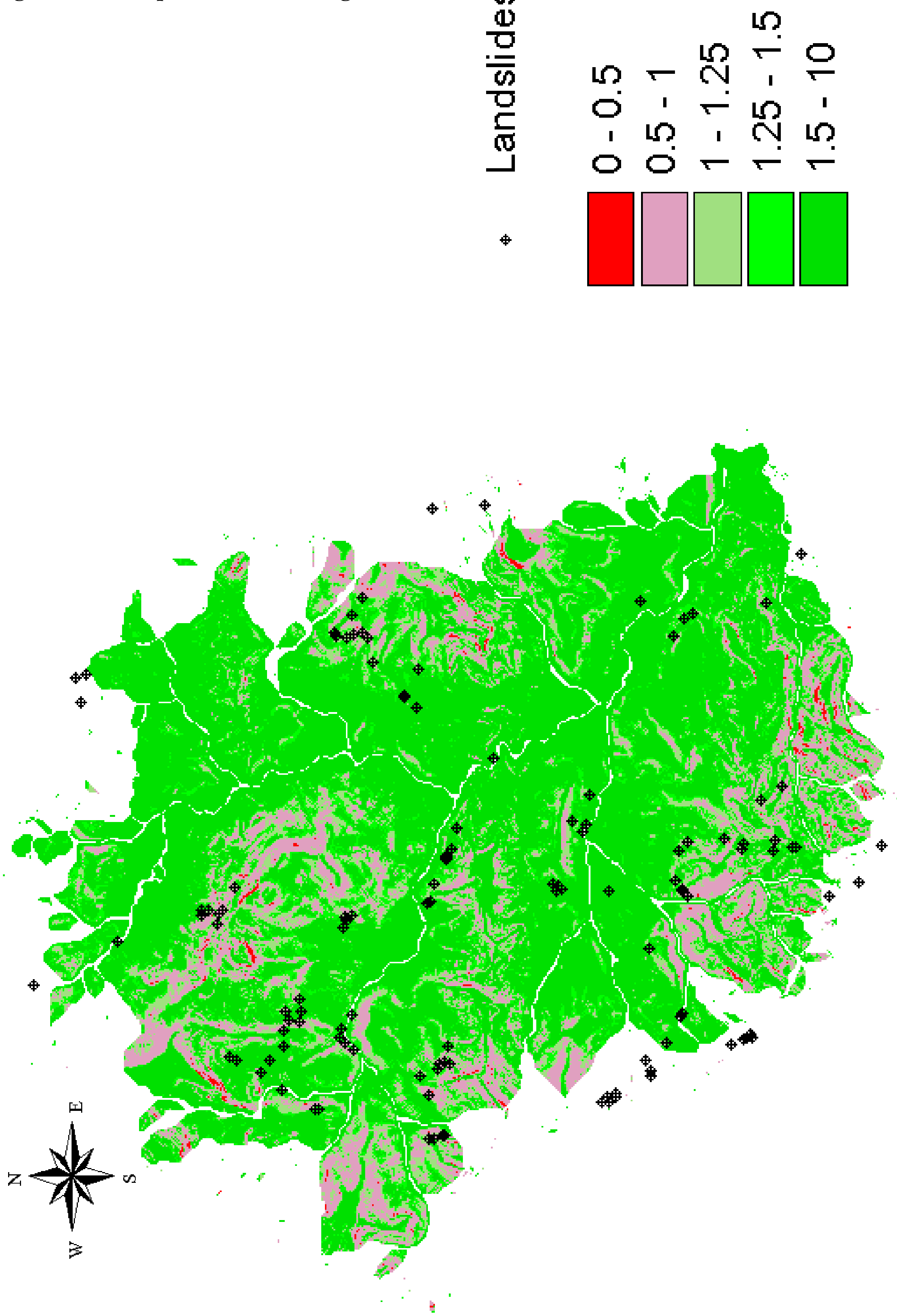


Figure 6: SI map for default settings.



4.2 The ArcWofE Modeling

The outputs from the ArcWofE modeling are more complex to interpret as compared to SINMAP. SINMAP delivers values based on a stability index. Classes are fixed, the results from the calculations are simply associated with the respective class. In ArcWofE, the results are probabilities. Problematic is the issue from what probability on an area can be considered to be at risk. Helpful here are two things. First, the prior probability that has been calculated by the program gives an aid. The prior probability (p_p) is the probability to find a landslide on a unit area randomly selected from the study area (BONHAM-CARTER *et al.*, 1989; PACK *et al.*, 1998a; RAINES *et al.*, 2000). The value is calculated by dividing the number of landslides (l_n) through the number of unit areas (u) found in the study region, thus $p_p = l_n/u$. For a unit area setting of 0.1 km², the prior probability is 0.0421; for a unit area setting of 1 km² it is 0.4212, or ten times higher because the amount of unit areas is ten times lower. If the posterior probability (p_{post}) of a unit area is higher than the prior probability, this allows the conclusion that it is more likely to find a landslide as compared to a purely random selection. Vice versa, if the posterior probability is lower, the area seems to expect less than by chance landslides. The magnitude of these expectations is expressed in the difference between the posterior probability and the prior probability. For evaluation purpose, the results were reclassified into five classes, similar to the results of SINMAP. Class one (1) shows the lowest probabilities, class five (5) the highest. Class five is thus the class with the highest expectations regarding future landslides according to the results from ArcWofE modeling. This classification is of course relative. To allow a bias free comparison, the equal interval classification method (ESRI, 1996a) was chosen. This classification method splits the range of the probabilities from each map into five equal classes. The area of each class was extracted to allow further comparison.

Various combinations of evidential themes were evaluated to identify the setup for the final analysis. Criteria to select this ideal combination included comparison of the conditional independence and the significance of the respective evidential theme. If two evidential themes of the same topic (e.g. the land use evidential theme based on land use with original classification and the one based on the reclassified map) are employed into otherwise unchanged conditions, the one yielding a higher significance value will be chosen. Regarding the evidential themes where a selection was necessary, the following selections were made:

1. Slope aspect: Aspect value 3 yields higher significance values, value 2 is discarded.
2. Slope angle: The evidential theme based on the statistical evaluation shows a clearly higher significance and is chosen over the evidential theme based on observations.
3. Land use: The land use map based on the user defined classes (reclassified) is chosen over the one derived from the original classification.
4. Elevation and Roads: These evidential themes show comparably low significance values below 1.9 but are included. Low significance values also indicate that the themes do not add much to the final result. As they are not expected to ad a faulty bias, the choice is made to include them in the final analysis.

Accordingly, the response theme is created with:

1. Land use, based on the reclassified map (ex_l-use);
2. Soil, 1 : 500,000 (ev_soil);
3. Soil, 1 : 50,000 (ev_soil2);
4. Rivers (ev_rivers);
5. Slope aspect (ev_aspect), value 3;
6. Slope angle (ev_slope), based on the statistical results;
7. Elevation (ev_eleva); and
8. Roads (ev_roads).

This combination of evidential themes has a conditional independence value of 0.88. Values below 1 indicate that one or more evidential themes are not completely conditionally independent (PACK *et al.*, 1998a). During the selection analyses, some analyses were also done with a unit area setting of 1 km² for comparison. This revealed that the conditional independence values are also influenced by the unit area setting. Conditional independence is more difficult to meet with smaller unit areas. If the assumption of conditional independence is not satisfied, the posterior probabilities will be too large in some parts of the map (BONHAM-CARTER *et al.*, 1989) and should rather be thought of as relative favorabilities (RAINES *et al.*, 2000).

Posterior probabilities of the landslides

As in SINMAP, only 60 % of the landslide points were used while building the evidential themes and the response theme. In total, 63 % of the points used throughout the modeling process show a posterior probability that is higher than the prior probability, as compared to only 50 % of the remaining points held back for evaluation purposes. This refers to about 58 % of all points being located in areas classified with a posterior probability larger than the prior probability. ArcWofE also calculates the uncertainty of the values. It is listed in form of variation of the respective value. If this variation is deducted from the posterior probability and thus minimum values are computed and used in the evaluation procedure, the overall fit is reduced to about 42 % of the landslides with posterior probabilities higher than the prior probability. On the opposite, when these values are added, about 70 % of the points show posterior probabilities higher then the prior probability.

Reclassification of the posterior probability map in five classes with the equal interval classification system (ESRI, 1996a) leads to a distribution of probabilities and classes as described in Table 8 (p. 57). It should be noted that the underlying classification is a working classification only. It may be modified according to individual needs. The class boundaries are independent from the prior probability and rely solely on the range of the posterior probability. This choice was made to ease comparison also in regard to the results from SINMAP.

Interesting is the pyramid-like area distribution, with the highest proportion in the range of the lowest probabilities (Table 8). However, the boundary of class 1 is about three times as high as is the prior probability. About 74 % of the landslides fall into class 1. 32 landslides, about 26 % of all landslides, are captured within classes 2 to 5. With about 15.15 km², these classes combined have a landslide density of about 2.1 landslides/km², compared to 0.69 landslides/km² as an average for the total study area when computed with all recorded landslides.

The map is illustrated in Figure 7 (p. 56). The values represent probability values as they have been described before.

Figure 7: Posterior probability map.

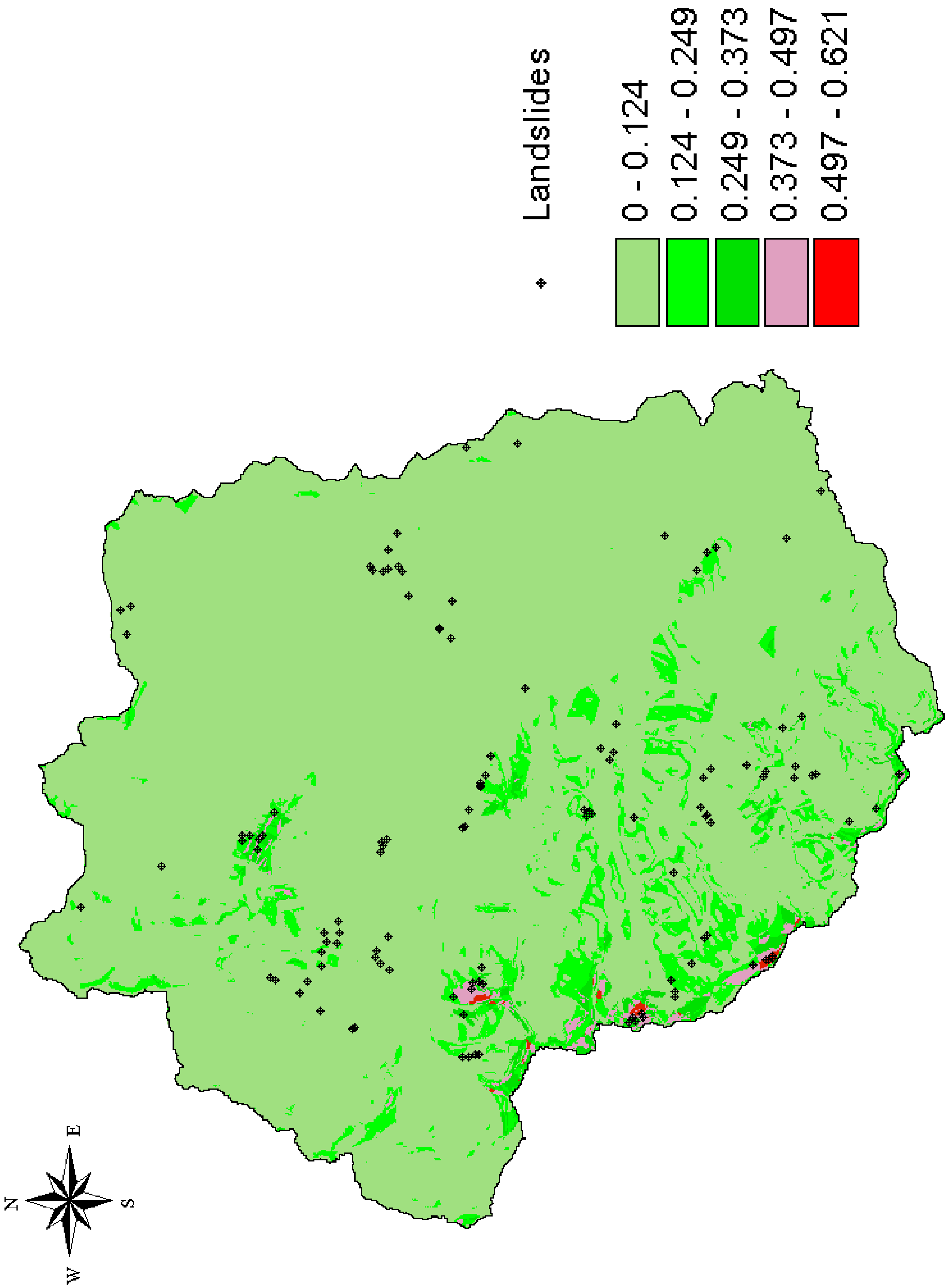


Table 8: Classification of the posterior probability map and the area allocated per class. Classification was done with equal intervals in ArcView (ESRI, 1996a).

Class	Posterior Probability		Area		Landslides (no.)	
	from	to	(km²)	(%)	input	evaluation
1	0	0.124	158.15	91.3	50	39
2	0.124	0.249	11.38	6.6	11	14
3	0.249	0.373	2.42	1.4	4	1
4	0.373	0.497	1.15	0.7	5	1
5	0.497	0.621	0.2	0.1	3	3

Contributions of the evidential themes

The final result is computed by combining the evidence from all evidential themes. For this purpose, all classes of each evidential theme undergo a weighting process. The results are then added to form the final probability map. The contribution of each evidential theme is expressed by the „confidence value". This is equal to the Studentized contrast explained in chapter 3.

High confidence values document a high contribution towards the final result. This can be in several ways, by providing evidence for the occurrence of landslides, by providing evidence for their absence, or of course both. If an evidential theme with a high confidence value is exchanged or taken out of the final analysis, the result can be expected to change more significantly as compared to themes with small values. With regard to the confidence or Studentized contrast, again values below 1.96 indicate with $\alpha = 0.05$ that a theme does not add significant information to the final result (PACK *et al.*, 1998a).

The confidence value for each evidential theme is listed in Table 9 (p. 58), ranked from the highest to the lowest value. The river theme and the two soil themes show the highest values clearly above three. The aspect, slope, and land use theme also clearly contribute to the posterior probability. The road and elevation theme show a confidence value that is below 1.96, but remain part of the final analysis.

Table 9: The table shows the evidential themes and the respective Confidence value in a descending listing. The confidence value is a measurement of the contribution of an evidential theme or its importance for the final result.

Evidential theme[1]	**Confidence value[2]**
Ev_rivers	3.1705
Ev_soil	3.1362
Ev_soil2	3.1280
Ev_aspect	2.9910
Ev_slope	2.5202
Ex_l-use	2.1645
Ev_roads	1.8684
Ev_eleva	1.8506

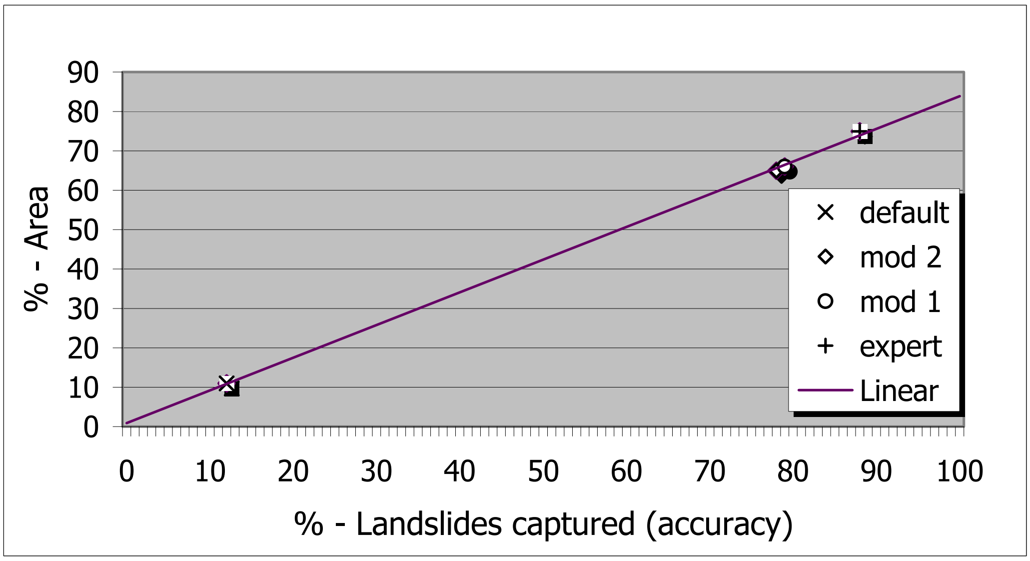
[1] same terminology as used in the description above;
[2] = Studentized contrast

5 Discussion

The results from the modeling are very clear and obvious. They are the result of a thorough investigation and combination of available materials. It could be observed during the field work that the study region does not experience landslides in what is considered normal years in terms of rainfall distribution. Existing landslides are a result of excessive rainfall during „Hurricane Mitch“ and caused a considerable amount of damage. One run with SINMAP was done with a parameter setting simulating a situation believed to be close to such normal years (default). The results from this run support these observations. None of the area is classified as 'defended'. The shares of the 'upper threshold' class are very low in all calibration regions too; most calibration regions show values below 0.5 % of the area in this class. The comparably high shares of the 'lower threshold' class can be linked to the lack of further calibration. This would be against the working theory of SINMAP. The results for the defended and upper threshold classes prove that very fine distinctions between the respective classes are possible. PACK *et al.* (1998a) also showed that good results can be achieved with SINMAP, when it is used in landslide risk assessment for normal climatic situations. The application of SINMAP for normal situations in the study area allows classifying the overall landslide risk as low in normal years.

When the parameters are changed to simulate extreme conditions, the models results seem promising at first. High percentages of landslides are captured as described in chapter 4. However, the amount of area classified as „critical“ is seriously overestimated. A comparison to results achieved by PACK *et al.* (1998a) underlines this observation. An overestimation of critical area does seriously reduce the utility value of the result, as key priority zones cannot be identified. This observation is backed by the ratio „percent landslides/percent area“ that is also illustrated in Graph 13. Although percent values are used, the ratio also indicates the landslide density and remains nearly constant. In other words, the model achieves the higher rate of captured landslides by including a higher proportion of area. The ability of the model to generally identify areas of higher risk is indicated by the landslide density that is clearly above average.

SINMAP works with a variety of general assumptions. These assumptions do not explain the landslide situation in the study area. In general, these assumptions are limited to situations with a foreseeable, hence understandable parameter behavior. During extreme meteorological conditions, the behavior of certain parameters, such as subsurface water flow, might take surprising or unexpected turns. It is reported from a study in the Mettman Ridge, Oregon, USA that subsurface water movements following extreme rains exceeded the assumed amounts by far and tremendously increased pore pressure (G-O.DE, 2002). GLADE (2000) models only the soil water status during landslide triggering rainfalls, with special emphasis on prior rains and resulting soil water status over time. He realized that not only the absolute amount of rain in a certain period but mainly the rainfall pattern were among the key driving forces for landslides in different regions of New Zealand. Including described phenomena into the simulations would not only require climatic data and soil property information in a detail far beyond the data available for San Dionisio, but also exceed the capabilities of SINMAP. ZINCK *et al.* (2001) mention that the complexity of the processes and interactions, and the catastrophic character of landslide events make it difficult to work with deterministic based models. Methods of determinism also do not account for small disturbances of various kinds and thus cannot reflect the chaotic behavior of landslides according to QIN *et al.* (2002).



Graph 13: The graph shows the relation between landslides captured and area classified as unstable for all four runs of SINMAP. The marked points represent default values, expert settings and modification 1 and 2 (points from left to right). The line is the (linear) trendline.

The results from ArcWofE do not allow a direct comparison between the individual modeling steps. All processing and pre-evaluation is designed to lead to a final model. The results are comparably easy to understand but difficult to compare as described in chapter 4. In the final result about 60 % of the landslides are captured in areas allocated a probability higher than the prior probability. Problematic is the question of how to account for the uncertainty. Also, including the 40 % of the landslide points held back for evaluation increases the number of known landslides that form the basis to calculate the prior probability. As a result, the prior probability would increase; the posterior probabilities however remain unchanged (KEMP *et al.*, 1998; RAINES *et al.*, 2000). In this study, all landslide points are compared to the original prior probability.

Interesting is the pyramid-like area distribution, with the highest proportion in the range of the lowest probabilities. Distribution pattern like this are desired, because they clearly mark out areas of high priority and thus show a high utility value. Problematic for the results here is that about 74 % of the landslides fall into class one. A total of 32 landslides, about 26 % of all landslides, are captured within classes two to five. With about 15.15 km², these classes combined have a landslide density of about 2.1 landslides/km², compared to 0.69 landslides/km² as an average for the total study area when computed with all recorded landslides. With a share of 8.7 % of the total study area and high landslide density values, the utility value of these results moves into the desired direction. ArcWofE seems to be more successful in pinpointing critical area than SINMAP. The disadvantage of the result is that only 26 % of the known landslide points are captured within this area, questioning the relevance. If the results are used to e.g. promote land management implications, or to derive decisions for certain prohibitive measures, still a large number of landslides cannot be accounted for.

Reasons may include that the driving forces have either not been fully accounted for. The question must be allowed whether sufficient identification and implementation of all relevant data is possible. Purely probabilistic based models are often found to predict approximate regions of landslide risk but without accounting for certain finer scale instability patterns that play an important role (GRITZNER *et al.*, 2001). These authors expect more linking of stochastic and deterministic (process) approaches in the future, but found that the ability of such models to make accurate prediction is seriously dependent on the type, resolution, and quality of data available at landscape scale. ZINCK *et al.* (2001) mention that probabilistic approaches lack important deterministic capabilities because they are built on cause-effect relationships. They do not account for the role played by what they call „the activating factors“, nor do they simulate or explain any of the mechanisms involved. This, so is the conclusion of ZINCK et al. (2001), does not meet the predictive purpose of the modes.

6 Conclusion

SINMAP is able to distinguish between areas at higher risk and areas at lower risk. The results obtained allow assuming that key „activating factors“ are not encountered for, or, in other words, landslides in extreme events behave different or are triggered by more complex interactions. The assumptions underlying SINMAP are too general considering the high spatial variability of the parameters and their behavior in extreme situations. As a result, the utility value of the information gained is low and unsatisfying. SINMAP is an insufficient tool to model landslide situations caused by extreme events and should not be applied to such situations. SINMAP has proven to be a useful tool for land use and other planning personnel if it is applied to standard situations. The deterministic background is unable to capture the bandwidth of factors related to landslides caused by extreme events and/or the magnitude of variation in the parameters. As a result, landslide risk in the study area is seriously overestimated. This is especially unsatisfying, because SINMAP is a comparably easy to apply tool with limited, easy to satisfy data demand. It leads to rapid results and should be considered where there are general landslide risks that cause significant damage and landslides following extreme events are not of primary concern.

The results generated by ArcWofE are different. At least some utility value can be gained. Problematic is its limitation to the top ranking classes that do not account for the majority of landslides. As a consequence of an application of the results, the relevance and impact of the decisions derived must be questioned. In general, ArcWofE can be considered a powerful tool for data analysis but is highly dependant on the quality and scale of input themes. Commonly accepted input information hereby is unsuitable to generate the expected results. Promising are the experiences based on more complex approaches that include some deterministic considerations. Parameters are thereby modeled themselves and results later included into the probabilistic model. ArcWofE delivers a promising approach to combine evidence in order to predict point locations, such as landslides. Of great importance for a successful application is data in a high quality. Data selection poses the biggest problem. As common approaches to explain landslides do not succeed to predict landslides caused under extreme events, new data mining methods have to be applied and evaluated. This is a serious constraint towards readily available and easy to apply modeling and will delay a broad application.

In general, modeling limits regarding the prediction of landslides caused by extreme events do exist. These limitations too are a result of the failure of conventional approaches to explain landslides under extreme events. While the deterministic driven SINMAP approach fails to adequately explain the processes underlying landslides as experienced in the study area. The lack of knowledge of the primary causes of landslides triggered by extreme events also limits the success of ArcWofE. Without this knowledge, no identification of adequate input themes is possible. The application of simple and quick modeling approaches to assess landslides potentials and dangers, emerging as a result of extreme events, failed. The experience documented in the literature showed hereby that it is less difficult to match modeling results to a specific area and a specific case than to make the underlying method generally available.

7 Summary

Agricultural systems and the people depending on them are extremely vulnerable to any kind of surprising events. In recent history the number and frequency, but also the impact, of extreme climatical events increased. While events like droughts and floods are comparably easy to understand and tackled with technological improvements, other events, such as landslides, present themselves highly complex. Agricultural research is conducted frequently on-farm in representative study regions, but often no vulnerability analysis with respect to landslide occurrence exists. Here, a simple and easy to apply tool could add valuable information and conclude the efforts regarding (sustainable) land use planning.

GIS-based models are found and offered in increasing variety. Spatial information is often readily available to run GIS-based models for landslide prediction. Problematic is that most modeling approaches are based on common landslide risks. This raises the issue whether and how available GIS-based models or modeling approaches will account for landslide occurrences caused by extreme climatic events. Satisfactory results could form an attractive bridge to combine available material and resources to fields of growing interest. This issue was tackled in cooperation with CIAT for a benchmark watershed in San Dionisio, Department of Matagalpa, Nicaragua. Screening of available information resulted in even more information than required or suggested for most modeling approaches. A deterministic-based approach was represented by SINMAP (Stability Index Mapping, PACK *et al.*, 1998) and a probabilistic-based approach by ArcWofE (Weights of Evidence extension for ArcView; KEMP *et al.*, 1998).

The results show that common deterministic-driven approaches are insufficient and fail to adequately explain the processes underlying landslides caused by extreme events. To predict a landslide at a location that is stable under the common variation of climatic and other stresses, the model overpowers all stabilizing forces assumed by the program. A large amount of landslide captured goes along with an over proportional amount of area classified as critical. As a result, the utility value is unsatisfactory.

A limitation regarding probabilistic approaches is the lack of knowledge on the processes involved. Without this, an identification of adequate input themes is problematic. Probabilistic models correlate known landslide locations with classes of the input data. The known landslide locations are thereby used to identify classes that show a higher expectation of landslides and rank them against each other. This approach delivers more promising results, as especially very critical areas are identified. Still, the relation critical area/captured landslides is unsatisfying, but the user must be aware that his choice of input information is essential for the final result.

This opens perspectives for a more complex identification of processes and parameter driving landslides under extreme events. Their behavior may be modeled and the results included into the probabilistic model. This way, locally valid models may be established. Their demand of data, time, and resources is however excessive. Areas without a powerful project or donor will not be able to generate a landslide risk assessment.

Landslides caused by extreme events are not included in most studies. The problems encountered while trying to utilize a generally available tool with data that can be expected to exist, revealed that the complexity of the topic allows to match models and their results to a specific situation but makes it impossible at this time to make the underlying method generally available.

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