Bartın Orman Fakültesi Dergisi
2012, Cilt: 14, Sayı: 22, 12-23
ISSN: 1302-0943
EISSN: 1308-5875

LANDSLIDE RISK ASSESMENT USING SINMAP (BARTIN-SÖKÜ SAMPLE STUDY)

Tuğrul VAROL[*]
[*]Bartın Üniversitesi Orman Fakültesi Orman Mühendisliği Bölümü, 74100 BARTIN,
tvarol@bartin.edu.tr

ABSTRACT

SINMAP (Stability Index Mapping) software is an ArcView extension developed by Environmental Systems Research Institute (ESRI) that is used to evaluate landslide risk at basin scale. SINMAP classification utilizes stability index values calculated at basin scale. The theoretical basis of SINMAP is an infinite slope stability model. A digital elevation model (DEM) is used to identify variables such as slope, soil moisture, and flow directions; and also takes into account factors such as permeability, water retention capacity, friction and root structure that might affect slope status. However, various difficulties might be encountered in calculating certain variables, which are therefore characterized by standard distribution within certain limits based on soil, vegetation and geological data. The software allows interactive calibration of variables according to observed landslide distribution. Using the variables reduces the possibility of assigning a low stability index in areas where no landslides are observed, whereas the possibility of observing landslides in areas with low stability index can be increased. In this study, a model developed by Pack et al. (2001) is explained according to infinite slope stability model and topographic wetness index. These two components are used to define SI in Sökü Department of Forestry.

Key words: SINMAP, landslide, stability index, digital elevation model

1. INTRODUCTION

SINMAP is a mapping tool that uses an infinite slope model and also completes other existing methods (Montgomery and Dietrich, 1994). SINMAP derives a terrain stability classification based on certain basin characteristics such as topographic slope, material properties and climate. Each of these variables is numerically identified within the study area. Topographic parameters are automatically obtained from a digital terrain model. Other parameters are considered as uncertain are assigned a range within lower and upper limits. The primary output of this model approach is a stability index (SI), which is a numerical value used to classify terrain in each grid cell of the study area. This value is defined as the probability of estimating the standard distribution of parameters, expressed as a value between 0 and 1.

Terrain stability maps allow for identification and mapping of general class and areas in practice and also provide faster results in areas that require detailed evaluation (Ellen et al., 1993). Table 1 indicates classifications

---

Yazışma yapılacak yazar:tvarol@bertin.edu.tr
Makale metni 06.08.2012 tarihinde dergiye ulaşmış, 16.08.2012 tarihinde basım kararı alınmıştır

that can be identified in units of SI. Selection of points (1.5, 1.25, 1.0, 0.5, 0.0) is subjective, and requires reasoning and interpretation in terms of class identifications. Terms such as “stable”, “moderately stable”, quasi stable” are used to classify the study area according to the success of the model within determined parameter ranges. SI is also considered as a safety criteria providing the magnitude of factors (regional loads, road drainage and increased moisture due to the effects of pore pressure) that cause instability in the area (Pack et al., 1998). The terms “lower threshold” and “upper threshold” are used to characterize the regions with 50% lower or higher probability of instability according to parameter ranges determined by the model. In these regions, instability can occur in the absence of external factors, due to interactions between the parameters even within limits where uncertainty and variability can be determined (Pack et al., 2001). The term “defended slope” is used to characterize regions where, according to the types of parameters defined in the model, the slope is variable; and the model is inappropriate for cases of bedrock outcrops (Pack et al., 2001).

Table 1. Stability Classifications (Pack et al., 1998).

Condition	**Sınıfı**	**Predicted State**	**Parameter Range**	**Possible Influence of Factors Not Modeled**
SI > 1.5	1	Stable slope zone	Range cannot model instability	Significant destabilizing factors are required for instability
1.5 > SI > 1.25	2	Moderately stable zone	Range cannot model instability	Moderate destabilizing factors are required for instability
1.25 > SI > 1.0	3	Quasi-stable slope zone	Range cannot model instability	Minor destabilizing factors could lead to instability
1.0 > SI > 0.5	4	Lower threshold slope zone	Pessimistic half of range required for instability	Destabilizing factors are not required for instability
0.5 > SI > 0.0	5	Upper threshold slope zone	Optimistic half of range required for stability	Stabilizing factors may be responsible for stability
0.0 > SI	6	Defended slope zone	Range cannot model stability	Stabilizing factors are required for stability

A variety of methods are used to determine slope stability and landslide damage (Sidle et al., 1985), and can be classified (Montgomery and Dietrich, 1994) as follows:

(1) Area analysis using checklists to determine landslide-sensitive areas,

(2) Planning of models via landslide inventory analysis,

(3) Observation of areas of weak slope stability and analysis of factors that can be characterized in these areas,

(4) Utilizing criteria such as slope, lithology, terrain form and geological structure to classify stability,
(5) Incorporating models that use hydrologic simulations within probability analyses.

Each of these approaches has a significant role in practical applications. In recent years, the availability of Digital Elevation Model (DEM) data has led to the development of new methods (Carrara et al., 1991). Developments in Geographic Information Systems (GIS) are provide advantages in measuring topographic characteristics related to slope stabilization and landslide. GIS (Geographic Information System) technology is allows for the estimation and mapping of instability at DEM scale. Mapping studies with the most appropriate scales are reported to be those that can identify the exact locations of areas with landslide values of a special value in terms of land use (Dietrich et al., 1992; Wu and Sidle, 1995). Dietrich et al. combined an infinite slope stability model and hydraulic elevation model based on digital elevation classes. Wu and Sidle presented a more detailed version of this approach that also took into account other factors such as root resistance and cohesion.

2.STABILITY INDEX

Equation (1) is used to calculate stability index:

$$FS = \frac{C + \cos\theta\left[1 - \min\left(\frac{R}{T}\frac{a}{\sin\theta}, 1\right)r\right]\tan\emptyset}{\sin\theta}$$

(1)

Here, a and θ express basin area and slope derived from topography, respectively; C is an independent value obtained by combining soil cohesion and root resistance; tanϕ refers to friction angle; r represents water/soil concentration ratio; the unit of R/T is (m^{-1}) and refers to the ratio of water saturation duration of soil to soil permeability. These four parameters are manually entered to the model. Concentration ratio r is a constant, expressed as 0.5. However, due to variation in the other three values, variations occur in SI value along the lower and upper limits. Due to variations in these lower and upper limits, the distribution at this interval is considered to be uniform (Dietrich et al., 1993). When R/T=x, tanφ=t the standard distribution between the upper and lower limits is expressed as shown in Equation (2).

$C \sim U(C_1, C_2);\ x \sim U(x_1, x_2);\ t \sim U(t_1, t_2)$ (2)

The occurrence of the smallest C and t values (namely C_1, t_1) with the greatest x (namely x_2) value is explained as the most moderate scenario to identify variations in parameters. In the most moderate scenario, FS value is greater than 1 and is formulized as is Equation (3) (Dietrich et al., 1993):

$$SI = FS_{min} = \frac{C_1 + \cos\theta\left[1 - \min\left(x_2\frac{a}{\sin\theta}, 1\right)r\right]t_1}{\sin\theta} \quad (3)$$

For areas with less than 1 minimum factor of safety, there is a probability of failure. This is a special probability that might stem from variability in C, tanφ and T. If R characterizes moisture that might vary over time, this probability can be temporary. Therefore, the uncertainty in x value is the intersection of special and temporary probabilities. These regions are defined as ($FS_{min} < 1$) the distribution of C, x and t values (Equation 2).

$SI = \mathrm{Prob}(FS > 1)$ (4)

The best scenario is $C=C_2$, $x=x_1$, and $t=t_2$. This scenario refers to Equation 5.

$$FS_{max} = \frac{C_2 \cos\theta \left[1 - \min\left(x_1 \frac{a}{\sin\theta}, 1\right) r\right] t_2}{\sin\theta}$$

(5)

Where, if $FS_{max} < 1$

$SI = \mathrm{Prob}(FS > 1) = 0$ (6)

The regions with $SI > 1$ ($FS_{min} > 1$), $0 < SI < 1$ and $SI = 0$ ($FS_{max} < 1$) are presented in Figure 1. These regions are explained in terms of slope and water collection areas. This provides visualization to better understand the events.

3.DIGITAL ELEVATION MODEL

A DEM is constructed via the method described by O'Callaghan and Mark (1984), Marks et al. (1984), Band (1986), Jenson and Domingue (1988), Tarboton (1989), Tarboton (1997), Garbrecht and Martz (1997). This procedure involves four stages:

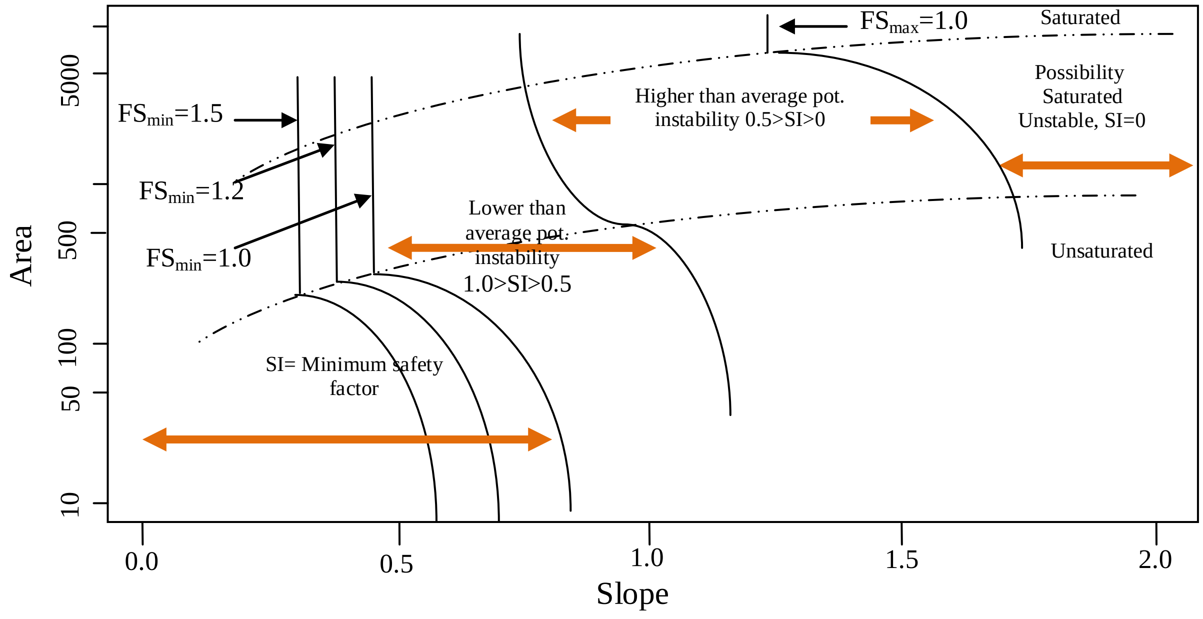


Figure1. Stability Index according to Terrain-Slope values

(1) Leveling of pit areas,
(2) Identification of flow directions and slopes,
(3) Identification of specific water collection basins,

(4) Identification of SINMAP stability index.

Topographical depressions were defined as the collection of grid elements surrounded by areas of higher elevation. These types of areas are not frequently found in topographic structure. They are generally believed to be formed artificially or to be the result of errors during formation of the DEM. The code of the lowest elevation in the neighborhood of these types of points is assigned to these points to eliminate these points (Jenson and Domingue, 1988).

The easiest and simplest method to determine flow directions involves the identification of flow from each grid cell to all of its eight neighbors (neighboring or transverse grid cells). The method developed by O'Callaghan and Mark (1984) is expressed as D8, and is widely used. The D8 approach has a disadvantage associated with the distribution of flow at 45 degrees to one of eight flow directions (Fairfield and Leymarie, 1991; Quinn et al., 1991; Costa-Cabral and Burges, 1994; Tarboton, 1997).

This led to development of other methods, including: multiple flow methods (Quinn et al., 1991; Tarboton, 1997), random direction methods (Fairfield and Leymarie, 1991) and grid flow tube methods (Costa-Cabral and Burges, 1994). SINMAP uses multiple flow direction developed by Tarboton (1979). In this method, angles of flow direction are determined such that they vary between 0 and 2π angles to east in a clockwise direction. This angle is measured and identified as the downslope direction within in a window of 3×3 grid cells with the target cell in the center. Flow directions and slope related to grid cells are taken as the direction and size of downslope flow in all eight surfaces. These values are obtained via the equation described by Tarboton (1997). On the other hand, in the upslope direction, calculations are made by using rewritten algorithms for a single direction (Mark, 1988). This system accepts that areas with the same characteristics contribute to the neighboring grid cell. The area of the study basin is determined as the section corresponding to the unit elevation of the number of cells corresponding to grid cell size.

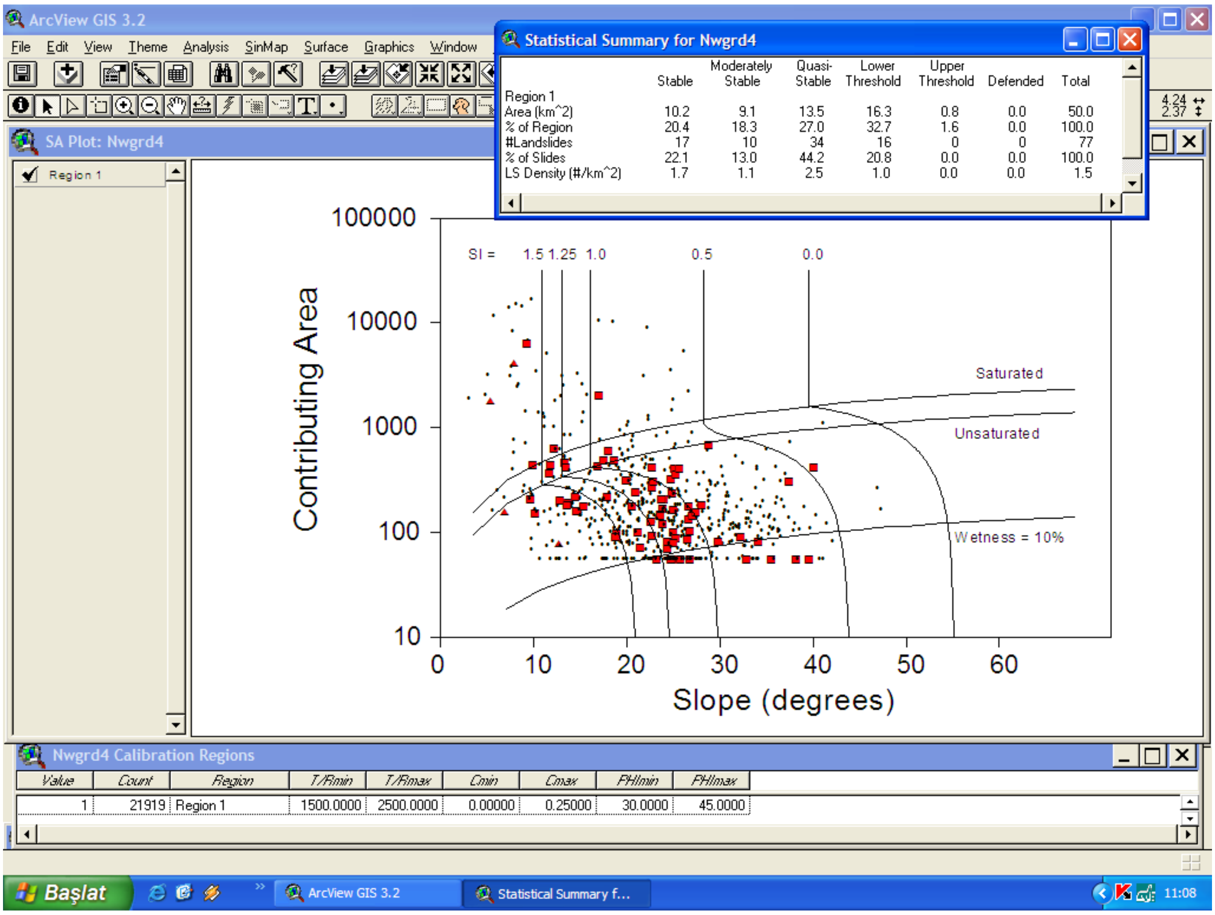
4.SINMAP SOFTWARE

SINMAP was developed to calculate moisture and stability index. The program can fulfill many tasks, such as slope calculation, identification of flow direction and area drainage at specific points. These processes are carried out via a DLL file.

Various calculations should be made on-screen or using printed maps in order to interpret outputs due to the structure of SINMAP analysis. Rather than standard geographic analysis tools, SINMAP uses the ArcView program developed by ESRI, and a Spatial Analyst tool that operates under this program. The abilities of ArcView program were performed by uploading additional sinmap.avx and sinmap.dll files. ArcView allows for modifications to program code and user interfaces via additional files such as avx. The additional SINMAP extension (sinmap.avx) provides the connection between sinmap.dll file and ArcView software. Various automated procedures such as creating maps and data preparation are used to convert SINMAP user data into graphical output. SINMAP output consists of maps showing areas of potential change. These maps are viewed in an image window within ArcView. Many tasks are related with SINMAP DEM map. These tasks include creation, usage and imaging of much geographic data. An base including both topographic and on-topographic (such as soil and hydraulic parameters) data is provided for the DEM SINMAP study. Other six grid cells obtained by the data in these cells are also used in fulfilling these tasks, and these cells provide flow direction, land slope, saturation, stability index and geographic distribution of topography. In addition to grid data, point data of landslide areas are required if users wish to compare estimated areas with actual landslide areas. DEM map images can be added as themes into these geographic data sets. Therefore, a full SINMAP study uses four CBS themes.

5.ANALYTICAL RESULTS

Stability index maps were produced using landslide inventory obtained from DEM and MTA (General Directorate of Mineral Research and Exploration) and SINMAP software. Analytical results are presented in Figure 2. The slope–terrain relationship is presented in a large window, calibration parameters of the use single calibration region are presented in a small window and statistical analyses are presented in the larger window.



Statistical Summary for Nwgrd4

Region 1	Stable	Moderately Stable	Quasi-Stable	Lower Threshold	Upper Threshold	Defended	Total
Area (km^2)	10.2	9.1	13.5	16.3	0.8	0.0	50.0
% of Region	20.4	18.3	27.0	32.7	1.6	0.0	100.0
#Landslides	17	10	34	16	0	0	77
% of Slides	22.1	13.0	44.2	20.8	0.0	0.0	100.0
LS Density (#/km^2)	1.7	1.1	2.5	1.0	0.0	0.0	1.5

Nwgrd4 Calibration Regions

Value	Count	Region	T/Rmin	T/Rmax	Cmin	Cmax	PHImin	PHImax
1	21919	Region 1	1500.0000	2500.0000	0.00000	0.25000	30.0000	45.0000

Figure 2. ArcView window showing SINMAP analysis results for Sökü District.

Analysis of soil and geological maps of the region reveals that the soil structure of the study area shows similarities within the basin; therefore, a single calibration region was used. In land analyses, it was observed that the geological structure of the area comprised homogenous sandstone and carbonated sandstone and texture structure with similar composition throughout the entire area. Using landslide inventory data that determines slope–terrain relationship, calibration parameters were produced via appropriate calibration curves. Although soil properties were not analyzed separately during calibration, soil friction values for 30- and 45-degree slopes were used when soil structure was analyzed with a realistic approach. These ratios were also used by Pack et al. (2001) During calibration, the limits of the T/R parameter were adjusted to 1500 and 2500. This value is equal to the length of the plane slope required to make 750–1250 m interval saturated at 30-degree slope. Figure 3 shows a section of the humidity map calculated by SINMAP analysis in the ArcView window.

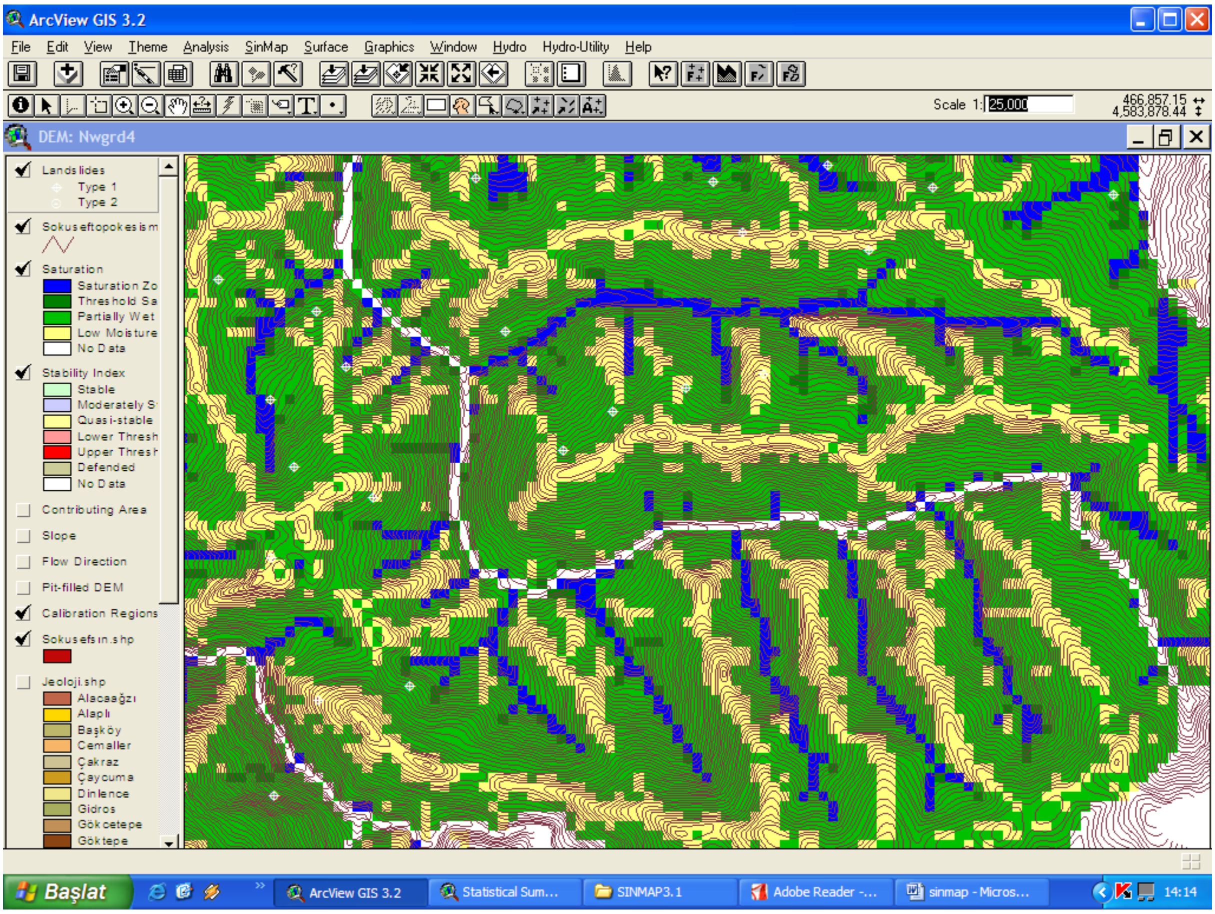


Figure 3. Image of a certain part of the humidity map obtained by SINMAP analysis in SÖKÜ region’s drainage in ArcView window.

Figure 4 shows an ArcView window with a section of the stability index map. As understood in statistical abstract in Figure 1, the “Quasi stable” stability index class (colored yellow in Figure 3) covers 34 landside value, representing 44.2% of total inventory. This class covers an area of 13.5 sqm, or 27% of the study area. Mean landslide density per sqm is 2.5. Values for this class were found to be 0.1 in Kilpala basin; 0.5 in Rose Creek basin; and 1.1–10.3 in various study areas in Burnt Creek basin. It was found that landslide density of “stable”, “moderately stable” and “lower threshold” classes were quite similar in the region, and that the density values of “upper threshold”, “defended” classes were zero.

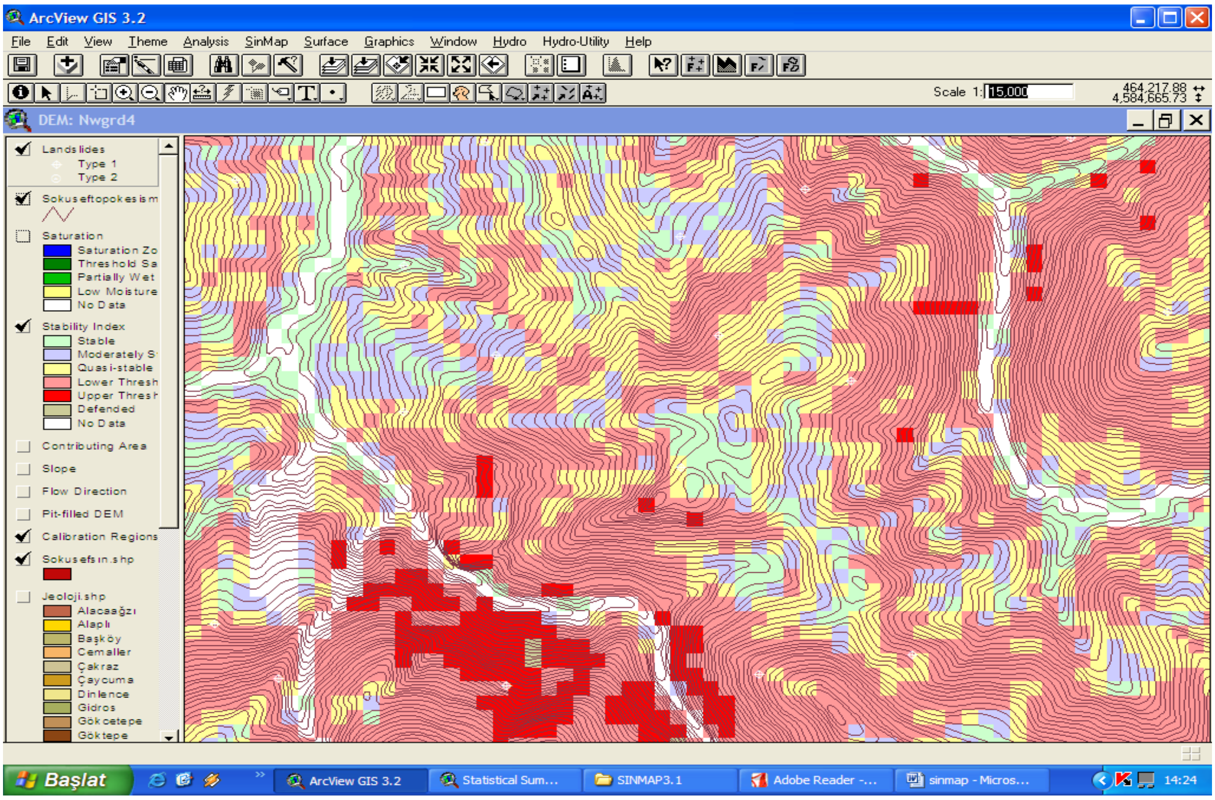


Figure 4. Image of a section of stability index map for Sökü region in ArcView window.

6.DISCUSSION

The study area Sökü Department of Forestry had a higher landslide percentage than other departments in Bartın Department of Forestry. Active landslides with a depth of more than 5 m cover the largest area in the study area (colored red in Figure 5; passive slides are colored orange). Active slides cover approximately 32.3% of the department area, and cover 46.8% of the area when combined with passive slides.

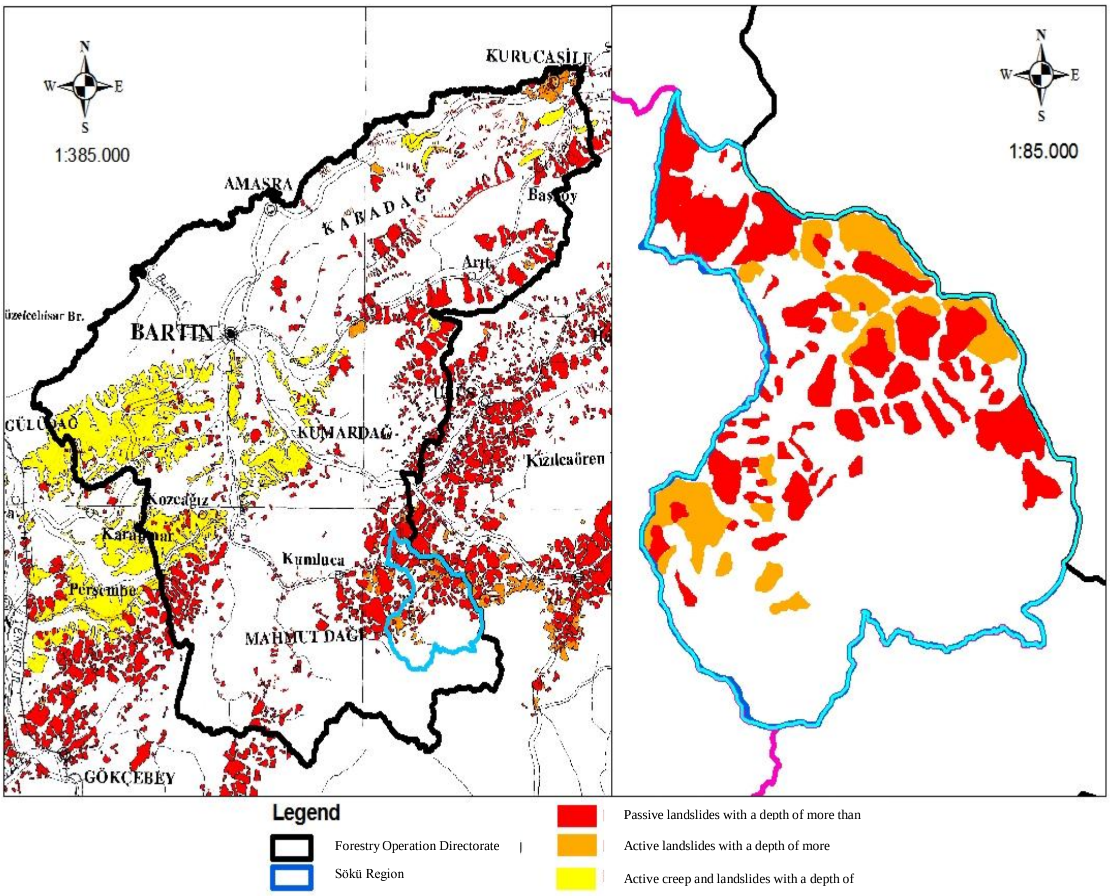


Figure 5. Image of active and passive landslide areas in Sökü region, and landslide areas in neighboring Department of Forestry.

It was observed that creep landslides were more common in Department of Forestry and that they mainly occurred in the Central Department of Forestry. Analysis of the neighboring forestry department revealed that the Kumluca region, which is the western neighbor of the study area, mainly consisted of passive slides with a depth of larger than 5 m; in parallel to the general structure of the Kozcağız region consisted of active creep with a depth less than 5 m.

Previous studies found that the majority of landslides occurred in steep rocky areas. Analysis of these areas found that soil structure varied and irregularities occurred in bedrock structure with increasing depth

(Montgomery and Dietrich, 1992). Land observations confirmed the same conditions for Sökü region. Therefore, in areas other than the forest area, outcropping of local bedrock might be due to landslides

.

It is reported in the literature that SINMAP analysis can clearly define landslide-sensitive areas, and can successfully identify landslide origin areas (Montgomery and Dietrich, 1992). On the other hand, the present analysis identified potential landslide areas at the tip of slopes during land survey of rocky areas that were previously not thought to be sensitive to landslides. Previous studies reported that landslides in these types of areas were caused by air conditions affecting the bedrock (Montgomery et al., 1991). The SINMAP methodology is inadequate to determine landslide-prone areas, because specific geological conditions cannot be modeled. To overcome these limitations, SINMAP should be combined with aerial photographs and land mapping techniques.

SINMAP theory is generally applied in planar slide and flows, and is not applied to rooted changes such as rotational, complex slides and complex landslides. The theory requires detailed terrain data to make calibrations. SINMAP methodology can be inadequate to explain certain conditions due to regional changes in geological conditions. It should therefore be supported with detailed data (aerial photographs, geological maps, etc.), and combined with various terrain mapping techniques.

Data required to apply the theory involves soil and air characteristics, which can show significant temporal and spatial variations. The theory does not require precise numerical data and also accepts a value range representing instability. Stability indexes obtained from analyses should not be interpreted as representing numerical precision, and should be considered as guides during risk periods.

SINMAP software uses grid-based data structures rather than vector-based polygons. The accuracy of the results mainly depends on the accuracy of DEM data input, and it is therefore important to make a great effort to collect accurate DEM and landslide inventory data.

The methodology used in the software can be obtained from (http://www.engineering.usu.edu/dtarb/) as a free extension of ArcView Spatial Analyst CBS software, published by Environmental System Research Institute (ESRI).

The SINMAP methodology was developed as a complement to terrain stability mapping studies, particularly applied by the forestry sector in British Columbia, Canada. It is reported in the literature that the theory can be applied in many other regions of Turkey that have physical geographic formations (Pack et al., 2001).

REFERENCES

Band, L. E., (1986), Topographic Partition of Watersheds with Digital Elevation Models, Water Resources Research, 22(1): l5-24.

Carrara, A., M. Cardinali, R. Detti, F. Guzzetti, V. Pasqui, and P. Reichenback, (1991) GIS Techniques and Statistical Models in Evaluating Landslide Hazard, Earth Surf. Processes Landforms, 16, 427-445.

Costa-Cabral, M. and S. J. Burges, (1994), Digital Elevation Model Networks (DEMON): A Model of Flow Over Hillslopes for Computation of Contributing and Dispersal Areas, Water Resources Research, 30(6): 1681-1692.

Dietrich, W. E., C. J. Wilson, D. R., Montgomery, J. McKean, and R. Bauer, (1992) Erosion Thresholds and Land Surface Morphology, Geology, 20, 675-679.

Dietrich, W. E., C. J. Wilson, D. R. Montgomery, and J. McKean, (1993) Analysis or Erosion Thresholds, Channel Networks and Landscape Morphology Using a Digital Terrain Model, J. Geol., 101, 259-278.

Ellen, S. D., R. K. Mark, S. H. Cannon and D. L. Knifong, (1993) Map of Debris Flow Hazard in the Honolulu District of Oahu, Hawaii, U.S. Geol. Surv. Open File Rep., 93-213, 25 pp.

Fairfield, J. and P. Leymarie, (1991), Drainage Networks from Grid Digital Elevation Models, Water Resources Research, 27(5): 709-717.

Jenson, S. K. and J. O. Domingue, (1988), Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis, Photogrammetric Engineering and Remote Sensing, 54(11): 1593-1600.

Marks, D., J. Dozier and J. Frew, (1984), Automated Basin Delineation From Digital Elevation Data,"Geo. Processing, 2: 299-311.

Mark, D. M., (1988), Network Models in Geomorphology, Chapter 4 in Modelling in Geomorphological Systems, Edited by M. G. Anderson, John Wiley., p.73-97.

Montgomery, D. R., R. H. Wright, and T. Booth, (1991) Debris Flow Hazard Mitigation for Colluvium-filled Swales, Bull. Assoc. Eng. Geol., 28, 303-323.

Montgomery, D. R., and W. E. Dietrich, (1992) Channel Initiation and The Problem of Landscape Scale, Science, 255, 826-830.

Montgomery, D. R. and W. E. Dietrich, (1994), A Physically Based Model for the Topographic Control on Shallow Landsliding, Water Resources Research, 30(4): 1153-1171.

O'Callaghan, J. F. and D. M. Mark, (1984), The Extraction of Drainage Networks From Digital Elevation Data, Computer Vision, Graphics and Image Processing, 28: 328-344.

Pack R.T., Tarboton D.G., Goodwin C. N. (1998), The SINMAP Approach to Terrain Stability Mapping, Paper Submitted to 8th Congress of the International Association of Engineering Geology, Vancouver, British Columbia, Canada.

Pack R.T., Tarboton D.G., Goodwin C. N. (2001), Assessing Terrain Stability in a GIS Using SINMAP, 15th Annual GIS Conference, Vancouver, British Columbia.

Quinn, P., K. Beven, P. Chevallier and O. Planchon, (1991), The Prediction of Hillslope Flow Paths for Distributed Hydrological Modeling Using Digital Terrain Models, Hydrological Processes, 5: 59-80.

Sidle, R.C., A.J. Pearce and C.L. O'Loughlin, (1985), Hillslope Stability and Land Use, Water Resources Monograph 11 Edition, American Geophysical Union, 140p.

Tarboton, D. G., (1989), The Analysis of River Basins and Channel Networks Using Digital Terrain Data, Sc.D. Thesis,Department of Civil Engineering, M.I.T., Cambridge, MA, (Also available as Tarboton D. G., R. L. Bras and I. Rodriguez-Iturbe, (Same title), Technical report no 326, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, M.I.T., September .

Tarboton, D. G., (1997), A New Method for the Determination of Flow Directions and Contributing Areas in Grid Digital Elevation Models, Water Resources Research, 33(2): 309-319.

Wu, W. and R. C. Sidle, (1995), A Distributed Slope Stability Model for Steep Forested Watersheds, Water Resources Research, 31(8): 2097-2110.