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LANDSLIDE HAZARD DUE TO EARTHQUAKES AND RAINFALL

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EARTHQUAKE INDUCED LANDSLIDES

When an earthquake occurs, the effects of earthquake-induced ground shaking is often sufficient to cause failure of slopes that were marginally to moderately stable before the earthquake.

Las Colinas neighborhood of Santa Tecla, El Salvador, Central America as a result of the M=7.6 earthquake of January 13, 2001.

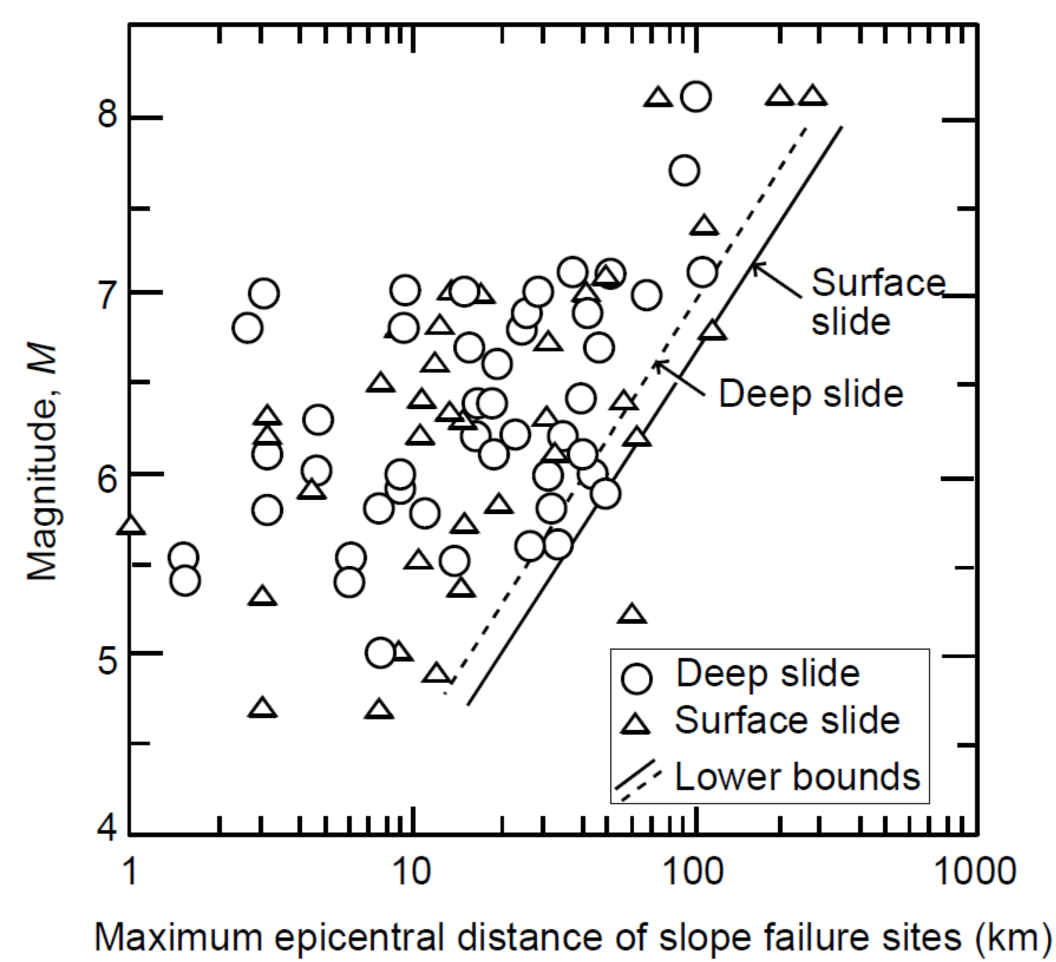
EARTHQUAKE INDUCED LANDSLIDES

More than half of all deaths in large (M>6.9) earthquakes in Japan between 1964 and 1980 were caused by landslides.

It is logical to expect that the extent of earthquake induced landslide activity should increase with increasing eartquake magnitude and there could be a minimum magnitude below which earthquake induced landsliding would rarely occur. Failure of slopes that are near the brink of failure under static conditions could be produced by quite weak earthquake shaking.

It is equally logical to expect that the extent of earthquake induced landslide activity should decrease with increasing source to site distance and that there could be a distance beyond which landslides would not be expected in earthquakes of a given size.

Similarly the area over which earthquake induced landsliding can be expected also increases with increasing earthquake magnitude.



Magnitude, M
8
7
6
5
4
1
10
100
1000
Maximum epicentral distance of slope failure sites (km)
Surface slide
Deep slide
Deep slide
Surface slide
Lower bounds

LANDSLIDE HAZARD ZONATION

SCALE OF MAPPING	INPUT DATA	METHODS
1:1.000.000-1:50.000 (regional scale)	Historical earthquakes and existing information Geological and geomorphological maps	GRADE 1 General Zonation
1:100.000-1:10.000 (medium scale)	Air Photos and remote sensing Field Studies Vegetation and precipitation data	GRADE 2 Detailed Zonation
1:25.000-1:5.000 (large scale)	Geotechnical investigation Analyses	GRADE 3 Rigorous Zonation

(modified according to ISSMGE, 1999)

GRADE 1

- ***Statistical methods***

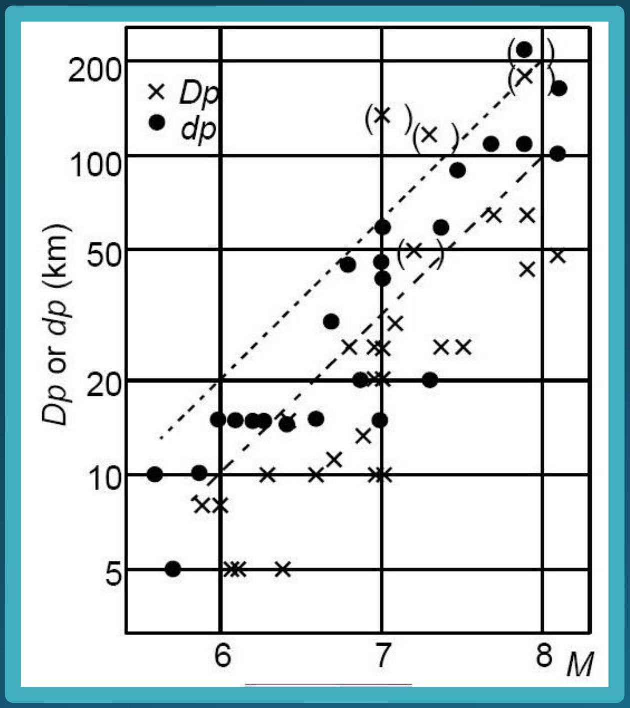
- ***Advantage:*** *The lowest cost but most cursory level of zonation*

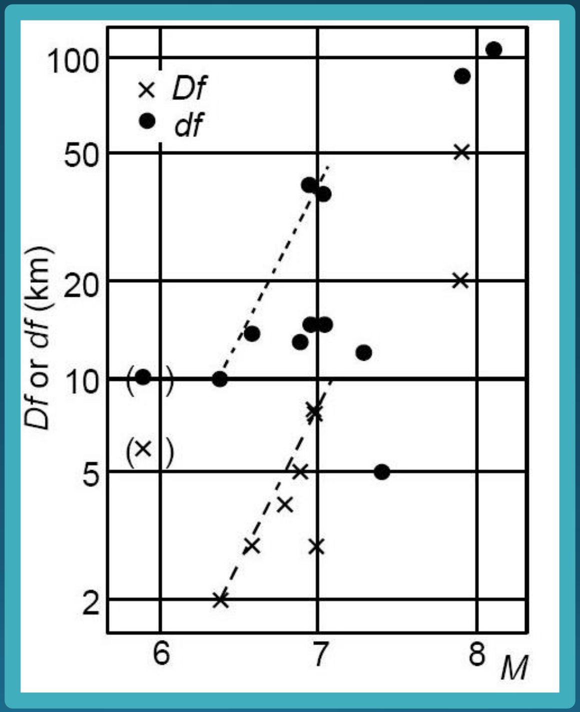
- ***Disadvantages:*** *do not incorporate local geology and soils*
  it is not appropriate for seismic microzonation

- ***Main Parameters:*** *Earthquake magnitude and Seismic Intensity (past earthquakes) or gw conditıons and rainfall patterns*

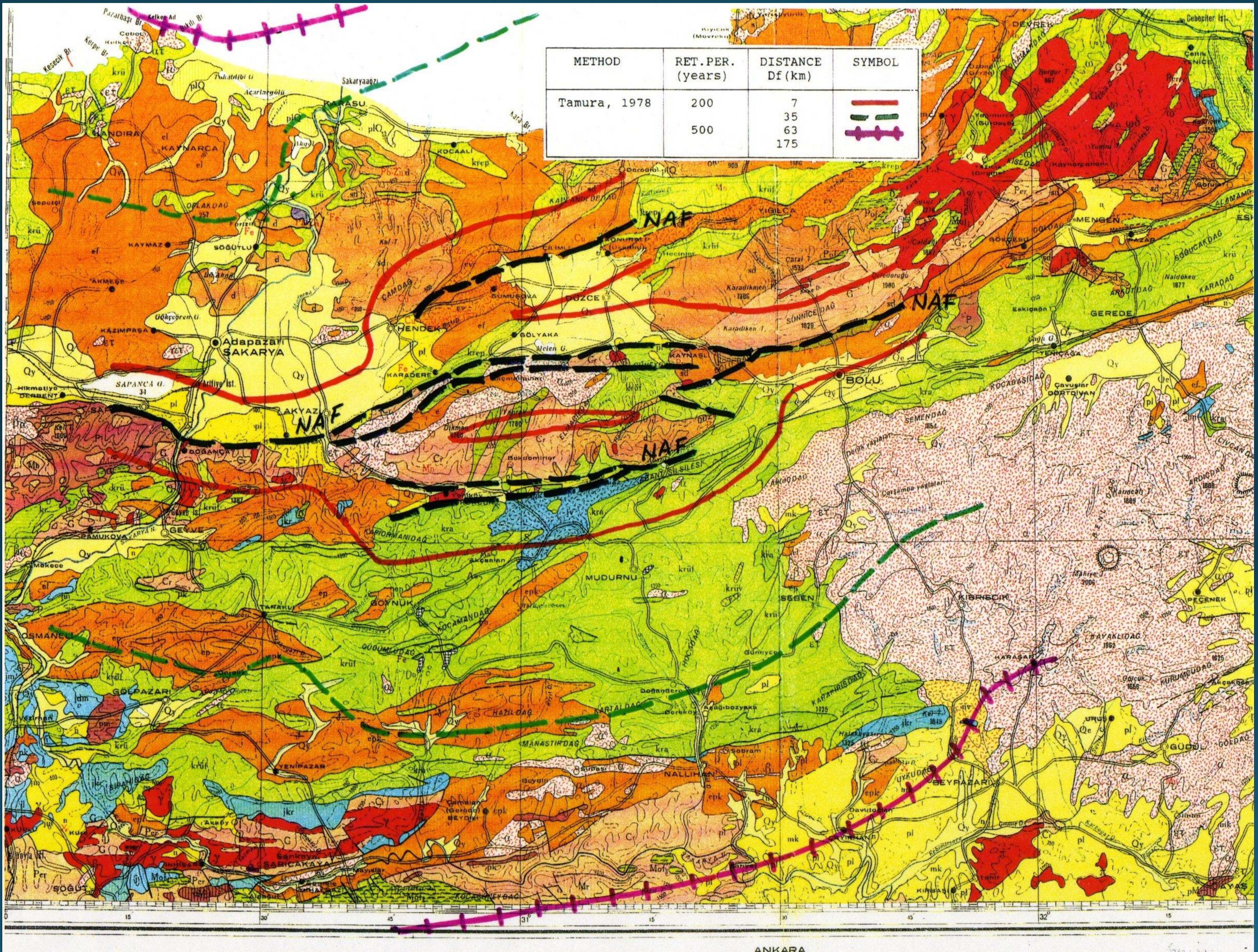
GRADE 1

Magnitude-Distance Criteria; screens the potential areas of slope instability using the relationship between magnitude and maximum distance from a fault or an epicenter.





The relationships btw magnitude and distance to slope failure in Japan from Tamura (1978)


METHOD
RET.PER. (years)
DISTANCE Df(km)
SYMBOL
Tamura, 1978
200
500
7
35
63
175
NAF
NAF
NAF
NAF
Adapazarı
SAKARYA
SAPANCA G.
HENDEK
DÜZCE
BOLU
GEREDE
MENGEN
KARASU
KOCAALİ
KAYNARCA
AKYAZI
GEYVE
PAMUKOVA
MUDURNU
GÖYNÜK
SEBEN
KIBRISCIK
GÖLPAZARI
OSMANELİ
TARAKLI
NALLIHAN
BEYPAZARI
GÜDÜL
YENİPAZAR
SÖĞÜT
DEVREK
YIĞILCA
GÖLYAKA
KAYNAŞLI
KARADERE
ANKARA

GRADE 2

- ***Statistical method***
- ***Basis:*** *addition to Grade 1 approach topographical and geological information (sometimes require additional field investigation)*
- ***Advantage:*** *more detailed informationthan Grade 1 approach*
- ***Disadvantage:*** *more expensive than Grade 1 approach*
- ***Main Parameters:*** *Earthquake magnitude and Seismic Intensity (past earthquakes)*

Method Proposed by Mora and Vahrson (1993):

- Mora and Vahrson (1993) developed a methodology depending on case studies of slope failures in historic earthquakes and also those induced by heavy rainfall in Central America in order to predict zones susceptible to slope failure. In this methods, factors related to slope stability analysis are classified into two main groups; those influencing the susceptibility and triggering ones. The former is composed of relative relief, lithologic conditions, and soil moisture and the latter one consists of seismicity and rainfall intensity. A degree of slope failure hazard is introduced by combining these factors as;

- $H_l = |S_r * S_l * S_h| * |T_s + T_p|$
- Where,
- H_l, is the landslide hazard index
- S_r, is the value of relative relief index.
- S_l, is the value of lithologic susceptilibty.
- S_h, is the value of index of influence of natural humidity of the soil.
- T_s, is the value of influence of seismic intensity.
- T_p, is the value of influence of rainfall precipitation intensity.

Method Proposed by Mora and Vahrson (1993):

Relative Relief Values (R_r) Values and Their Classes of Influence in Landslide Susceptibility (Mora and Vahrson, 1991)		
Relative Relief	**Susceptibility**	**Parameter, S_r**
0 – 75m/km²	Very Low	0
76 – 175	Low	1
176 – 300	Moderate	2
301 – 500	Medium	3
501 – 800	High	4
> 800	Very High	5

Classes of Average Monthly Precipitation (Mora and Vahrson, 1991)	
Average Monthly Precipitation (mm/month)	**Assigned Value**
< 125	0
125 - 250	1
250 <	2

Classification of Lithologic Influence, according to General Conditions, representative for Central America (Mora and Vahrson, 1991)		
Lithology	**Susceptibility**	**Value, S_l**
Permeable limestone, slightly fissured intrusions, basalt, andesites, granites, ignimbrite, gneiss, hornfels; low degree of weathering, low water table, clean – rugose fractures, high shear strength rocks	Low	1
High degree of weathering of above mentioned lithologies and of hard massive clastic sedimentary rocks; low shear strength; shearable structures	Moderate	2
Considerably weathered sedimentary, intrusive, metamorphic, volcanic rocks, compacted sandy regolithic soils, considerable fracturing, fluctuating water tables, compacted colluvium and alluvium	Medium	3
Considerably weathered, hydrothermally altered rocks of any kind, strongly fractures and fissured, clay filled; poorly compacted pyroclastic and fluvio – lacustrine soils, shallow water tables	High	4
Extremely altered rocks, low shear resistance alluvial, colluvial and residual soils, shallow water tables	Very high	5

Method Proposed by Mora and Vahrson (1993):

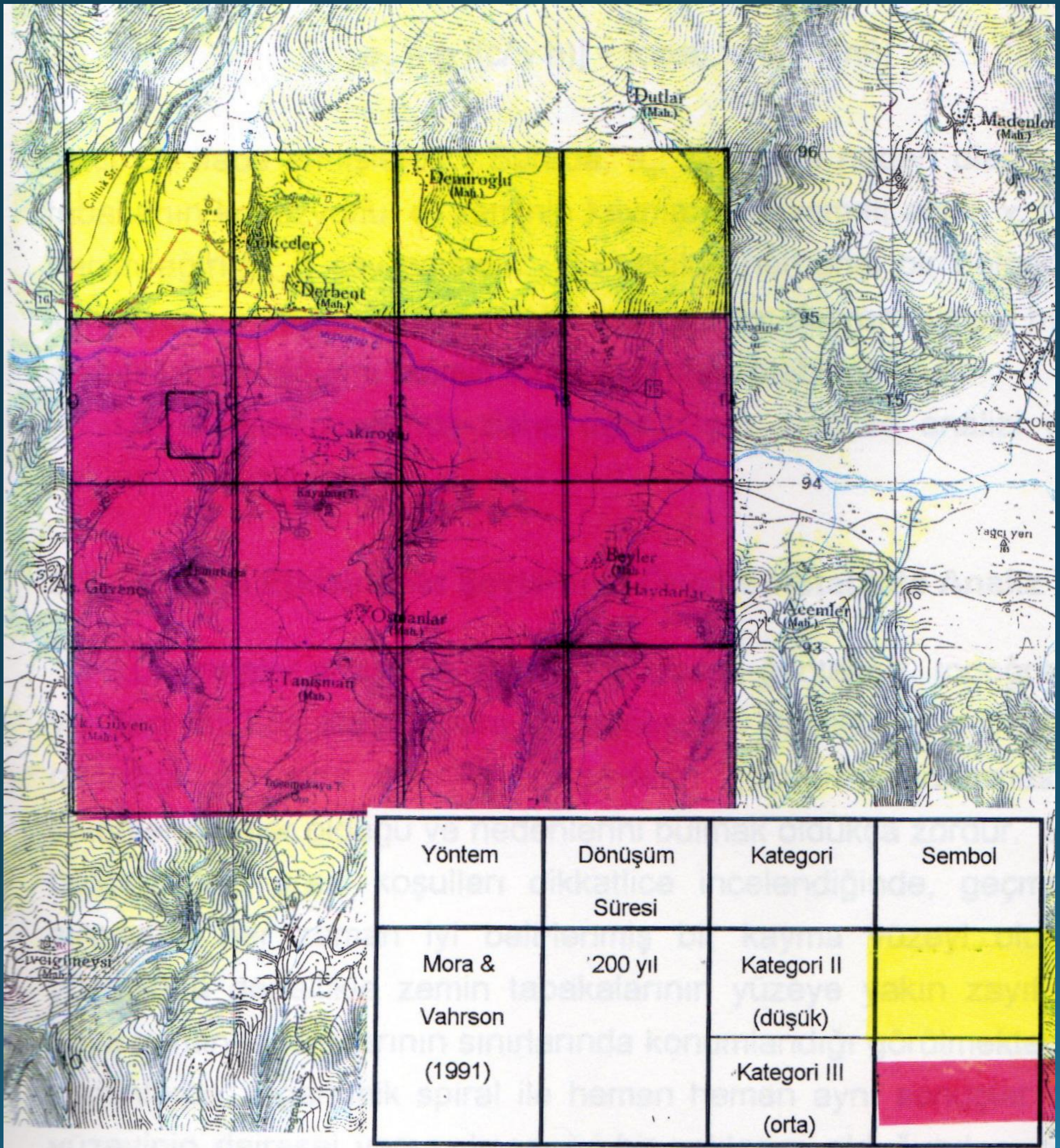
Weighting for Annual Precipitation (Mora and Vahrson, 1991)		
Summation of Precipitation Averages	**Susceptibility**	**Value, S_h**
0 – 4	Very low	1
5 – 9	Low	2
10 – 14	Medium	3
15 – 19	High	4
20 – 24	Very high	5

Influence of Seismic Intensity (Modified Mercalli Scale) as a Triggering Factor for Landslide Generation		
Intensities (MM) T_r = 100 years	**Susceptibility**	**Value, T_s**
III	Slight	1
IV	Very low	2
V	Low	3
VI	Moderate	4
VII	Medium	5
VIII	Considerable	6
IX	Important	7
X	Strong	8
XI	Very Strong	9
XII	Extremely Strong	10

Method Proposed by Mora and Vahrson (1993):

Influence of Rainfall Precipitation Intensity as a Triggering Factor for Landslides (Mora and Vahrson, 1991)			
Maximum Rainfall n > 10 years: T_r = 100 years	**Rainfall n<10 years; Average**	**Susceptibility**	**Value, T_s**
< 100 mm	< 50 mm	Very low	1
101 – 200	51 – 90	Low	2
201 – 300	91 – 130	Medium	3
301 – 400	131 – 175	High	4
> 400	> 175	Very High	5

Classes of the Potential Landslide Hazards, as Derived from Eq. (1.3.1) (Mora and Vahrson, 1991)		
Value from Eq. (1.3.1)	**Class**	**Susceptibility of Hazard**
0 – 6	I	Negligible
7 – 32	II	Low
33 – 162	III	Moderate
163 – 512	IV	Medium
513 – 1250	V	High
> 1250	VI	Verh High

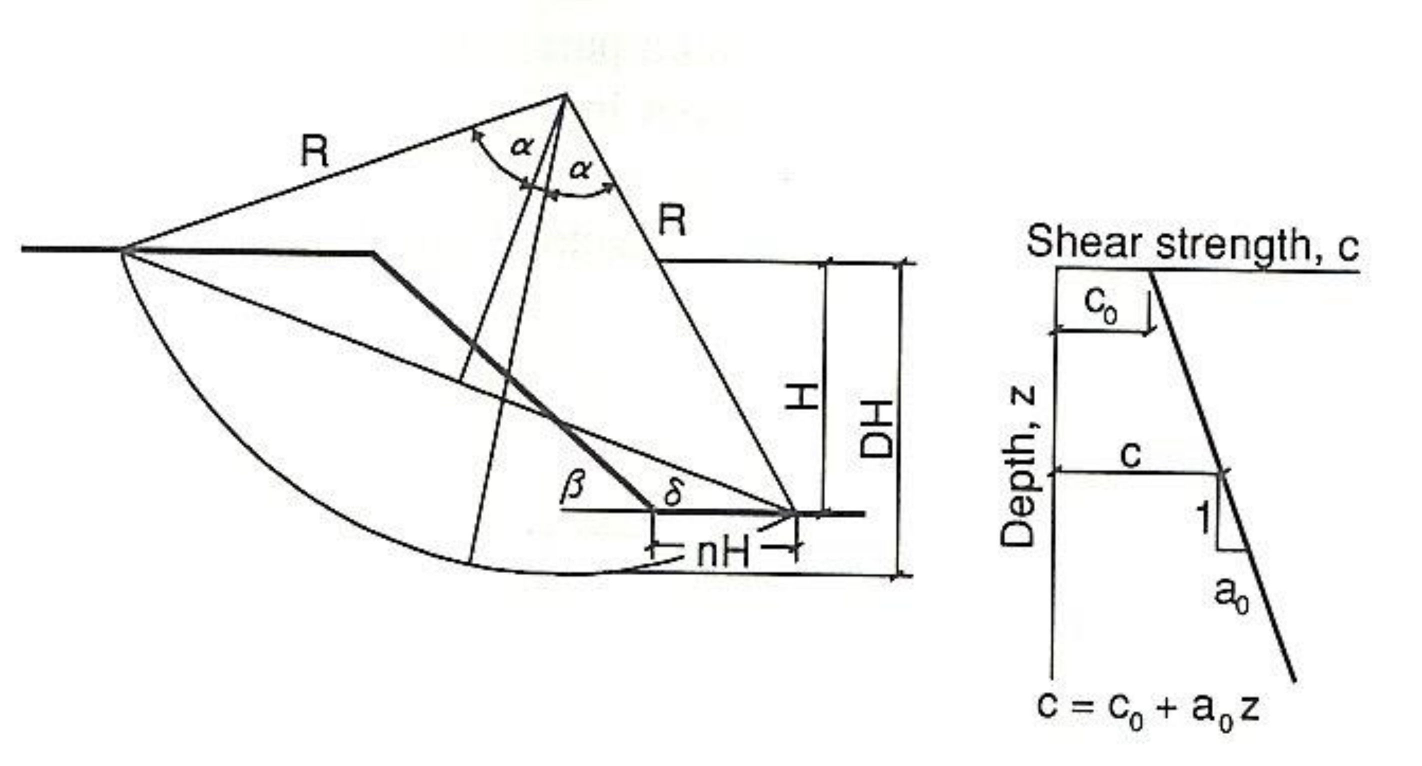


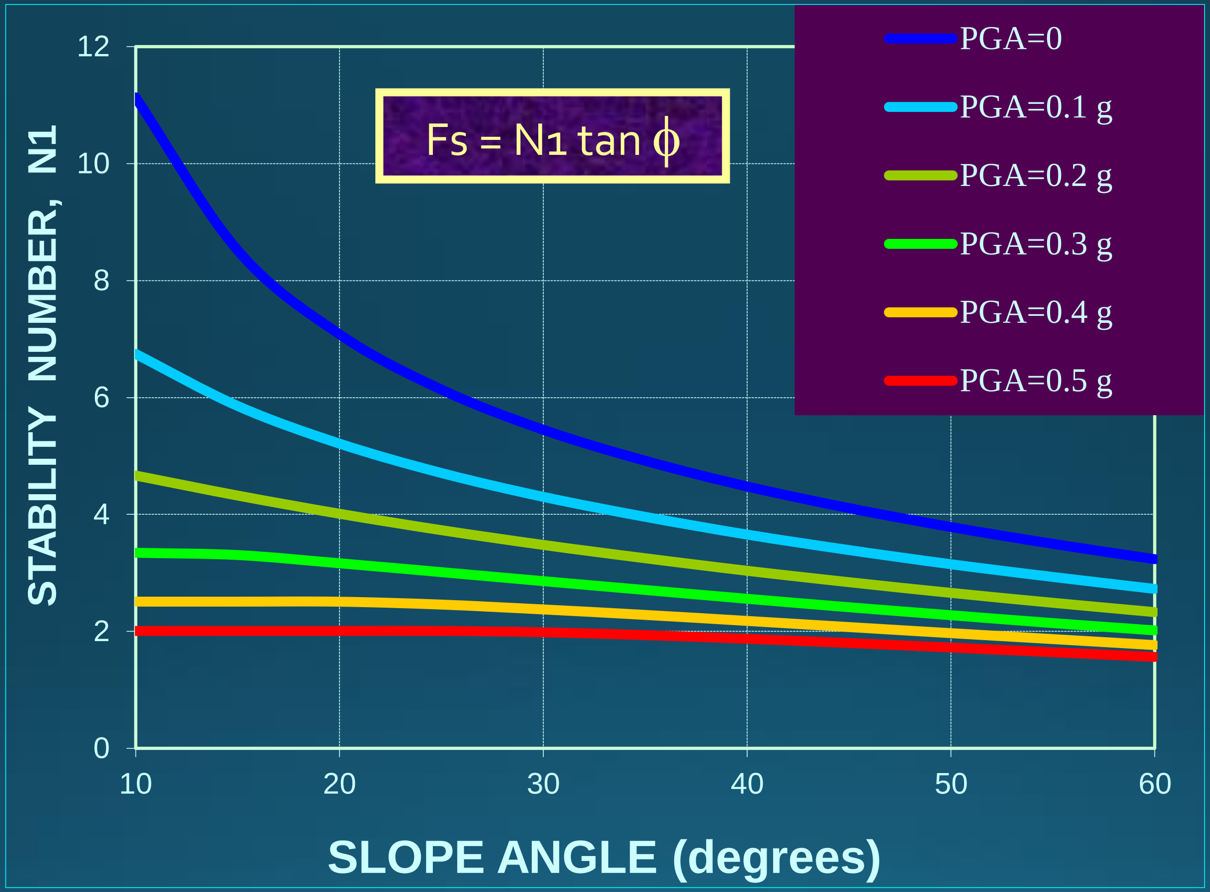
Yöntem	Dönüşüm Süresi	Kategori	Sembol
Mora & Vahrson (1991)	200 yıl	Kategori II (düşük)	
		Kategori III (orta)	

GRADE 3

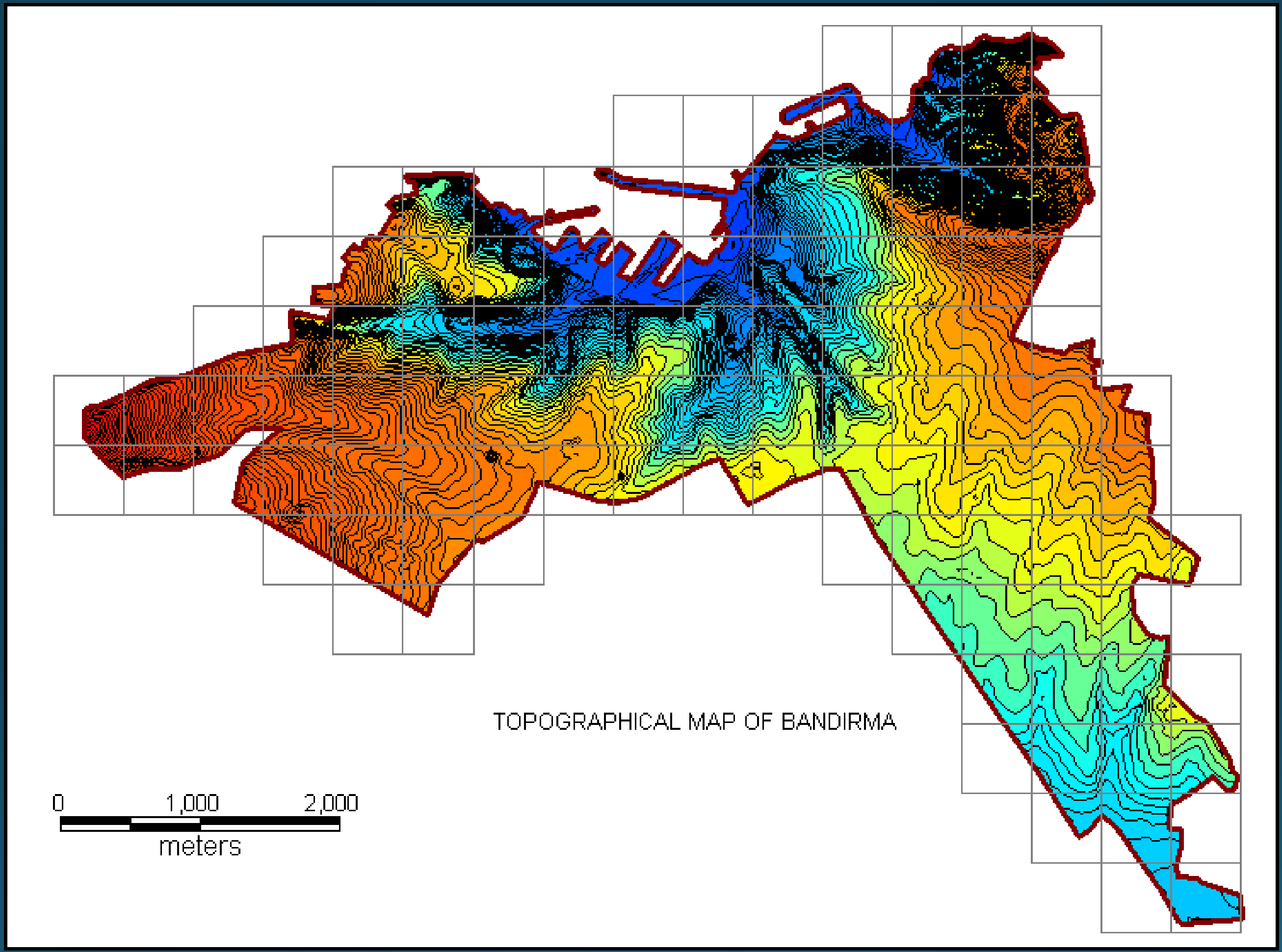
- ***Pseudo Statitic Approach and Sliding Displacement Method***
- ***Basis:*** *combination of Grade 1 approach, Grade 2 approach and geotechnical investigations*
- ***Advantage:*** *perform on a site specific basis & given a sufficiently detailed site investigation very reliable zonation maps*
- ***Main Parameters:*** *Critical Acceleration and Factor of Safety*

Siyahi ve Ansal (1993)

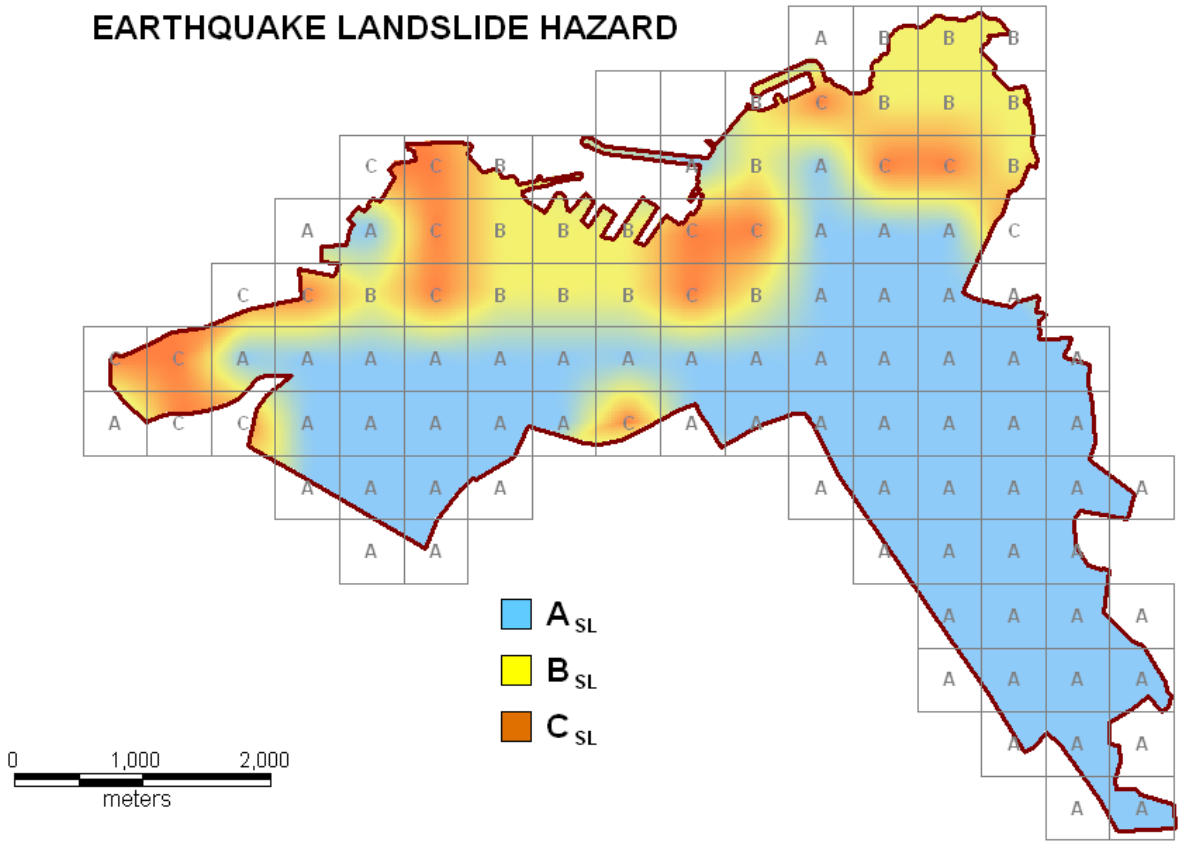




LANDSLIDE HAZARD DURING EARTHQUAKES


TOPOGRAPHICAL MAP OF BANDIRMA
0
1,000
2,000
meters

EARTHQUAKE LANDSLIDE HAZARD

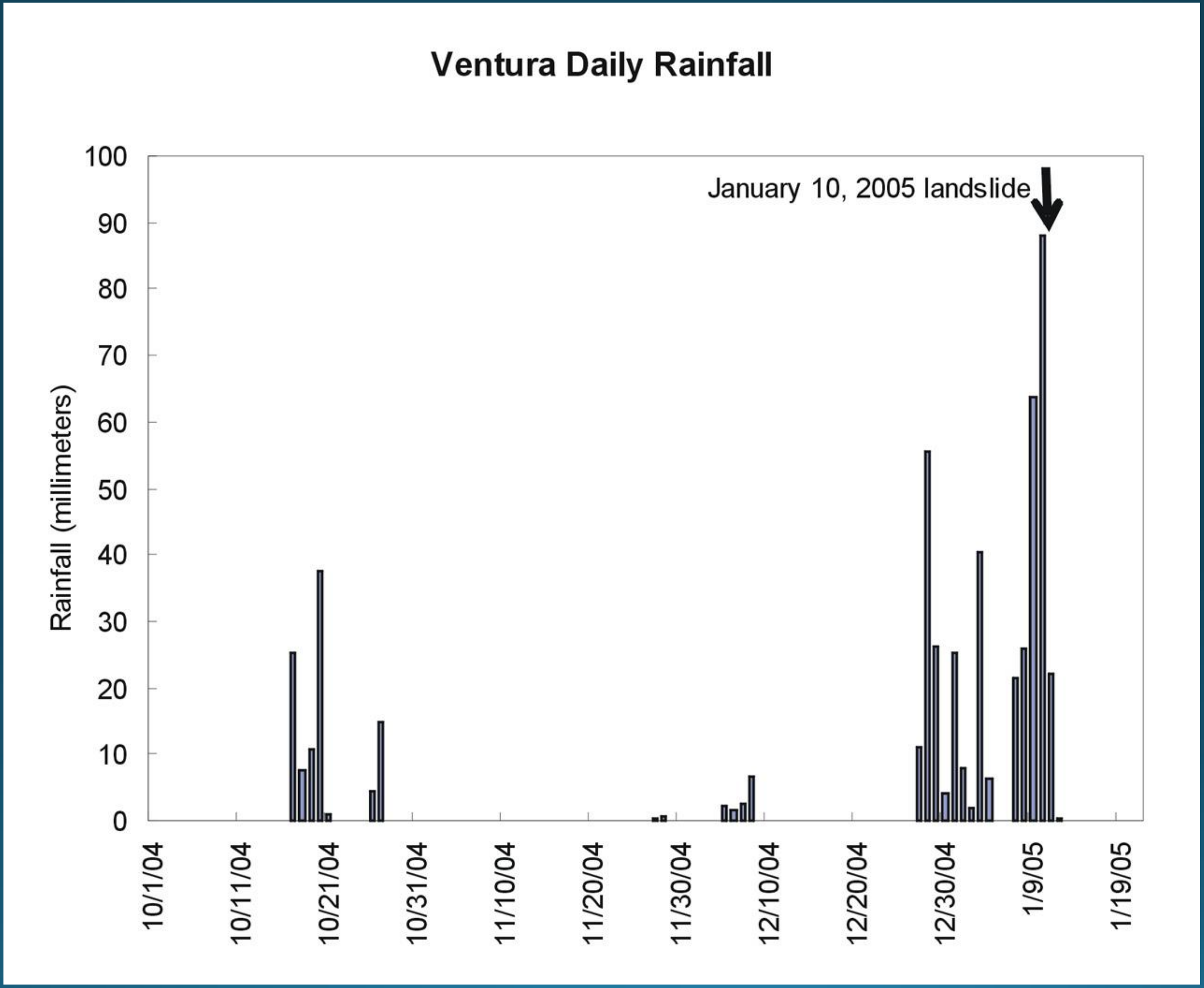


RAINFALL INDUCED LANDSLIDES

1. Topographical Methods
   a. *Method Proposed by O'Loughlin (1981) – (1986):*
   b. *Method Proposed by Montgomery and Dietrich (1994):*
   c. *Method Proposed by More and Vahrson (1993):*
2. Statistical Methods
   a. *Method Proposed by Papa M.N., Medina V., Ciervo F., Bateman A. (2013):*
3. Analytical Methods
   a. *Method Proposed by Iverson (2000)*
4. Numerical Methods
   a. *Method Proposed by Hills, Porro, Hudson and Wierenga (1989):*
   b. *Method Proposed by Lam, Fredlund and Barbour (1987):*

Photograph of the La Conchita, California landslide of 1995

Rainfall



Ventura Daily Rainfall
January 10, 2005 landslide
Rainfall (millimeters)
100
90
80
70
60
50
40
30
20
10
0
10/1/04
10/11/04
10/21/04
10/31/04
11/10/04
11/20/04
11/30/04
12/10/04
12/20/04
12/30/04
1/9/05
1/19/05

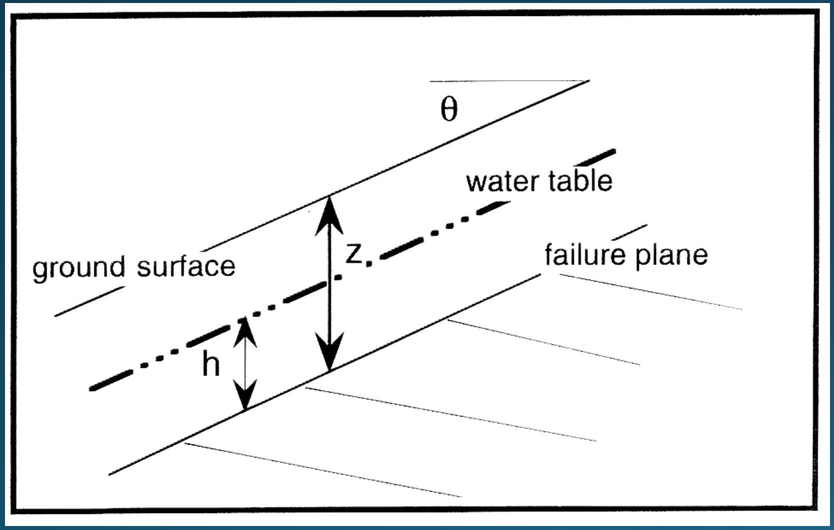
SHALSTAB

- SHALSTAB is based on an infinite slope form of the Mohr-Coulomb failure law in which the downslope component of the weight of the soil just at failure, t, is equal to the strength of resistance caused by cohesion (soil cohesion and/or root strength), C, and by frictional resistance due to the effective normal stress on the failure plane:

- $$\tau = C + (\sigma - u)\tan\phi \qquad (1)$$

in which s is the normal stress, u is the pore pressure opposing the normal load and tanf is the angle of internal friction of the soil mass at the failure plane. This model assumes, therefore, that the resistance to movement along the sides and ends of the landslide are not significant.

- A further simplification in SHALSTAB is to set the cohesion to zero..
- By eliminating cohesion, in Eq.1 in which **z** is soil depth, **h** is water level above the failure plane, r_s and r_w are the soil and water bulk density, can then be solved for **h/z** which is the proportion of the soil column that is saturated at instability:



$$\frac{h}{z} = \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right) \quad (2)$$

- This simple equation explicitly states that the soil does not have to be saturated for failure. While this is nearly always assumed when one analyzes a landslide scar, theoretically it is not necessary.
- Note that h/z could vary from zero (when the slope is as steep as the friction angle) to r_s/r_w when the slope is flat (tanq = o).
- An important assumption is that the failure plane and the shallow subsurface flow is parallel to hillslope, in which case h/z can only be less than or equal to 1.0 and any site requiring h/z greater than 1 is unconditionally stable - no storm can cause it to fail.

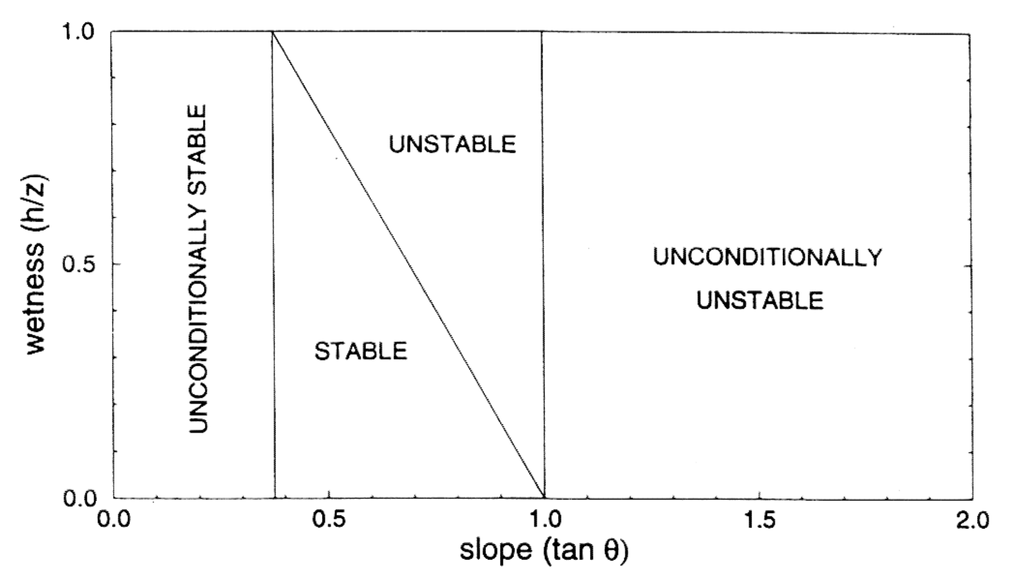


Figure 5.

- Note that four distinct stability fields emerge.
- Any slope equal to or greater than the friction angle will cause the right hand side of Eq (2) to go to zero, hence the site is unstable even if the site is dry ($h/z = 0$). We have called this "unconditionally unstable" and have found that it commonly corresponds to sites of bedrock outcrop.
- Because h/z cannot exceed 1.0 in this model, if tanq is less than or equal to tanf (1-(r_s-r_w)) then the slope is "unconditionally stable". We observe in the field that such environments can support saturation overland flow without failing.
- The two other stability states are "stable" and "unstable", with the former corresponding to the condition in which h/z is greater than or equal to that needed to cause instability (given by the right hand side of Eq (2)) and the latter corresponding to the case in which h/z is less than that needed to cause instability.

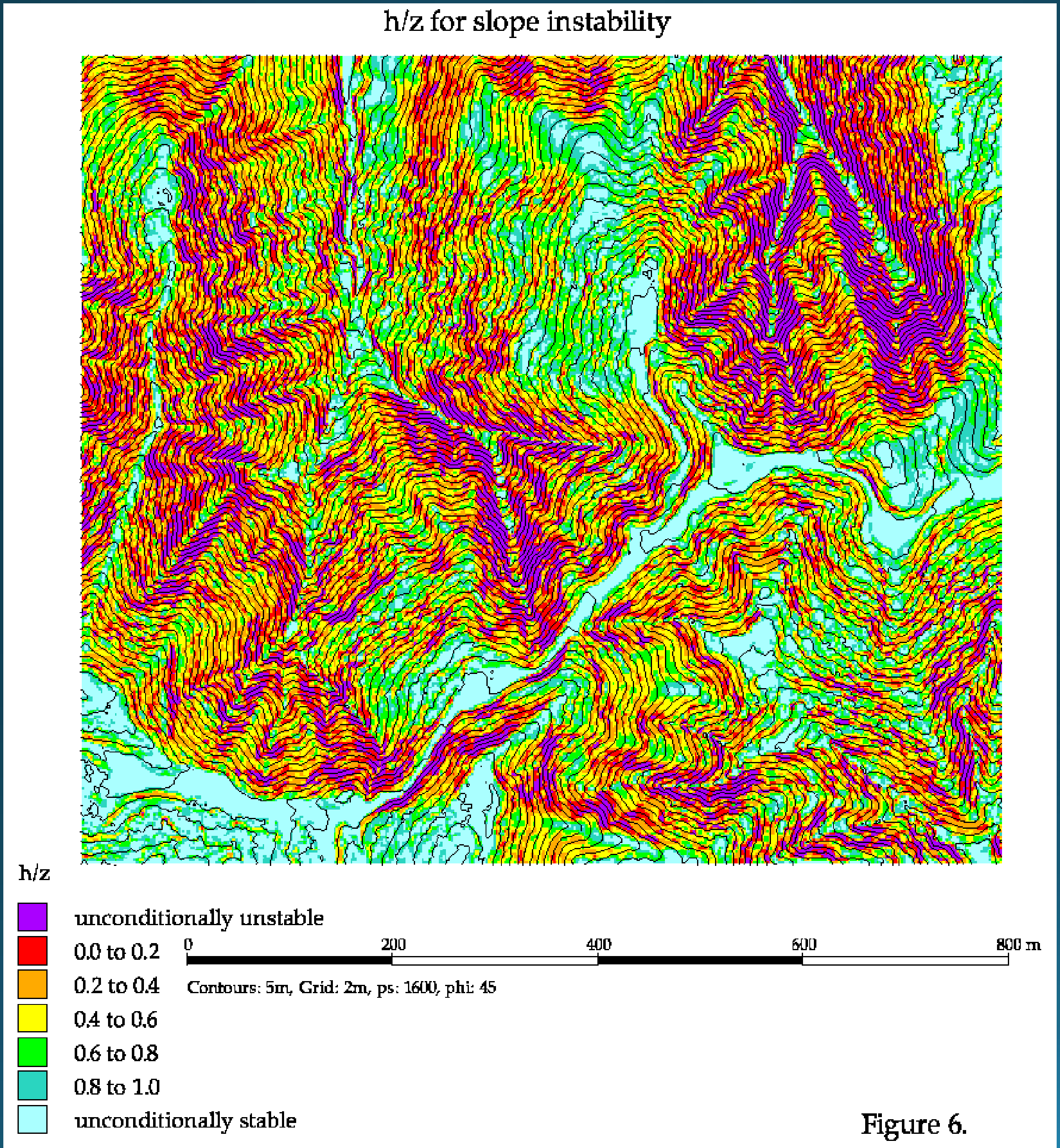


Figure 6.

The pattern of h/z needed for instability at the site in simply reflects the local slope: the steeper the hillslope the smaller the amount of water needed for instability.

Hydrologic model

- To model the hydrologic controls on h/z, we use a much simpler version of steady state shallow subsurface flow based on the work by O'Loughlin (1986) .
- It is assumed assumed that the steady state hydrologic response model mimics what the relative spatial pattern of wetness (h/z) would be during an intense natural storm which is not in steady state.
- This assumption would break down if precipitation events are sufficiently intense that thin soils on non-convergent sites can quickly reach destabilizing values of h/z before shallow subsurface flow can converge on unchanneled valleys. Efforts to model this effect do not show it to be likely (Hsu, 1994).
- Next Figure illustrates the geometry and routing of water off the landscape used in our hydrologic model. If we assume that there is no overland flow, no significant deep drainage, and no significant flow in the bedrock, then q, the effective precipitation (rainfall minus evapotranspiration) times the upslope drainage area, a, must be the amount of runoff that occurs through a particular grid cell of width b under steady state conditions.

- Using Darcy's law we can write that

- $$qa = k_s h \cos\theta \sin\theta b \qquad (3)$$

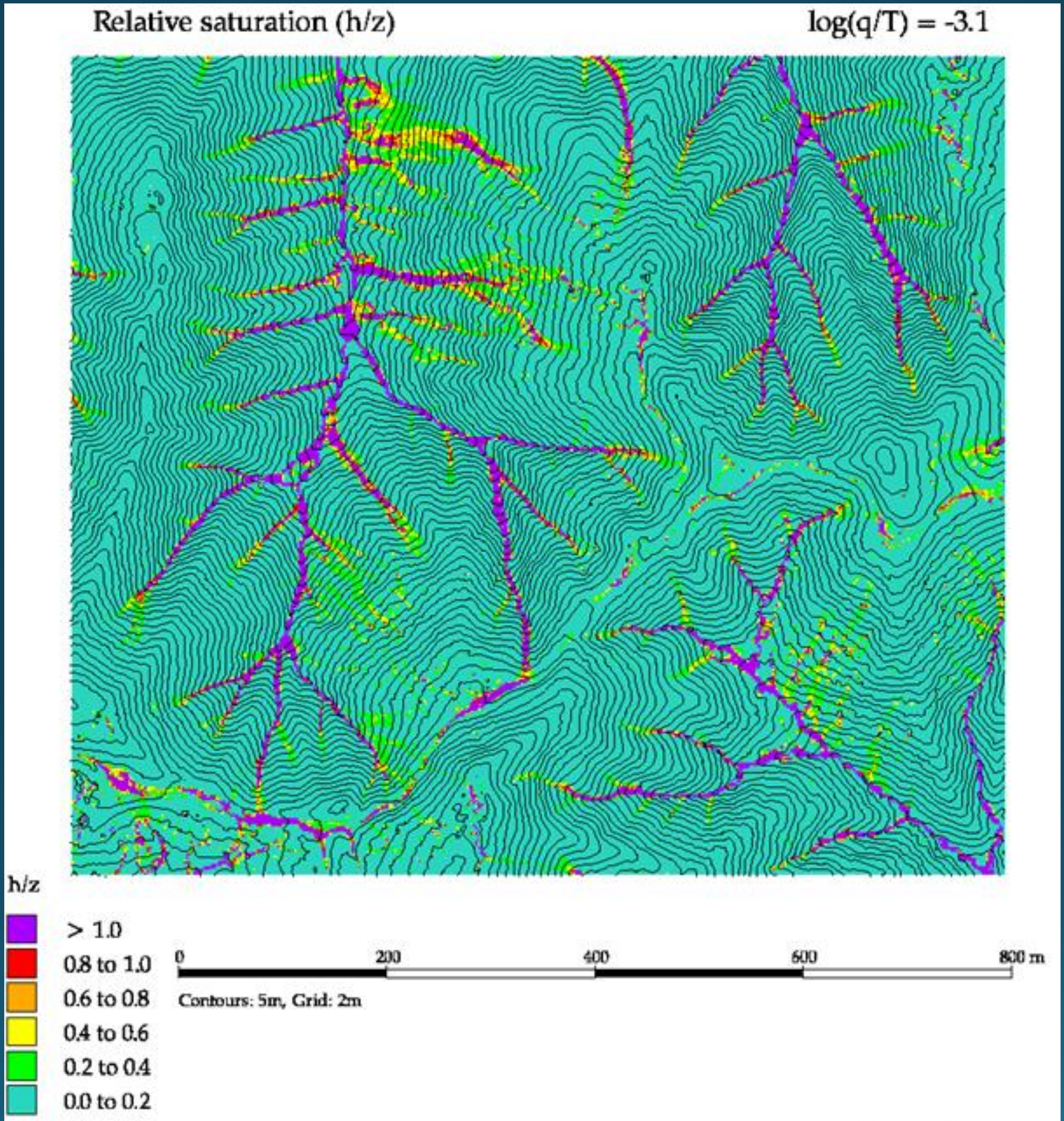
- in which **sinq** is the head gradient. At saturation the shallow subsurface flow will equal the transmissivity, **T**, (the vertical integral of the saturated conductivity) times the head gradient, sinq and the width of the outflow boundary, b and this we can approximate as follows:

- $$Tb\sin\theta = k_s z\cos\theta \sin\theta b \qquad (4)$$

- Combining (Eq.3) and (Eqç.4) leads to

- $$\frac{h}{z} = \frac{q}{T}\frac{a}{b\sin\theta} \qquad (5)$$

- Here we see that the pattern of h/z for a given storm is determined by two things: a hydrologic ratio and a topographic ratio.
- The hydrologic ratio is q/T. This ratio captures the magnitude of the precipitation event, represented by q, relative to the subsurface ability to convey the water downslope, i.e. the transmissivity. The larger the q relative to T the more likely the ground is to saturate, and clearly the greater the number of sites on a hillslope that will become unstable (where the h/z specified by (Eq.5) exceeds that given by (Eq. 2)).
- The topographic ratio, a/bsinq, captures the essential effects of topography on runoff. The effect of topographic convergence on concentrating runoff and elevating pore pressures is captured in the ratio a/b, which shows that the larger the drainage area relative to the cell width, the higher h/z.
- The steeper the slopes, the faster the subsurface flow and the consequently the lower the relative wetness defined by h/z.



Relative saturation (h/z)
log(q/T) = -3.1
h/z
> 1.0
0.8 to 1.0
0.6 to 0.8
0.4 to 0.6
0.2 to 0.4
0.0 to 0.2
0
200
400
600
800 m
Contours: 5m, Grid: 2m

Figure 9.

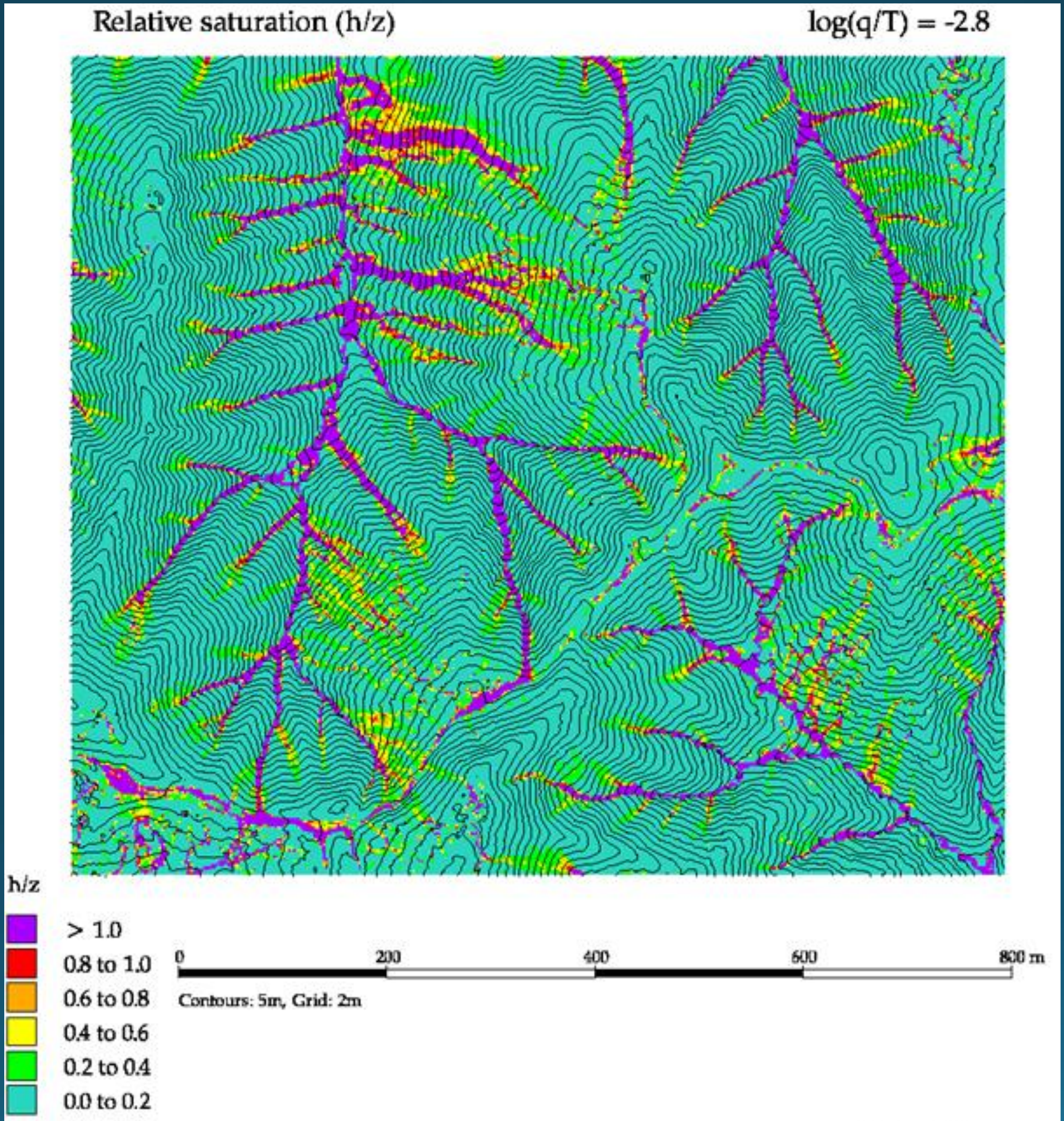

Relative saturation (h/z)
log(q/T) = -2.8
h/z
> 1.0
0.8 to 1.0
0.6 to 0.8
0.4 to 0.6
0.2 to 0.4
0.0 to 0.2
0
200
400
600
800 m
Contours: 5m, Grid: 2m

Figure 9.

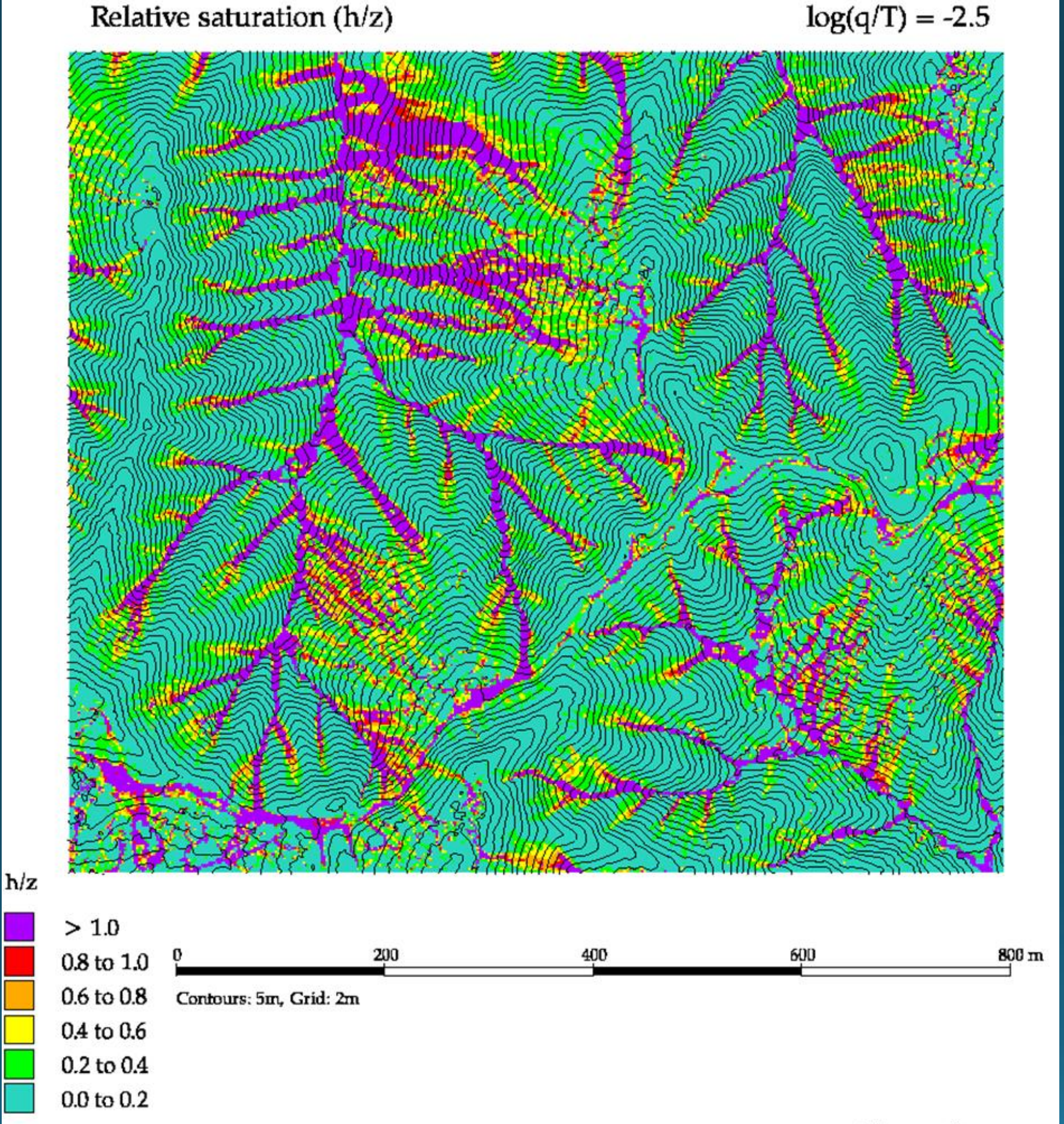

Relative saturation (h/z)
log(q/T) = -2.5
h/z
> 1.0
0.8 to 1.0
0.6 to 0.8
0.4 to 0.6
0.2 to 0.4
0.0 to 0.2
0
200
400
600
800 m
Contours: 5m, Grid: 2m

Figure 9.

Relative saturation (h/z) log(q/T) = -2.2

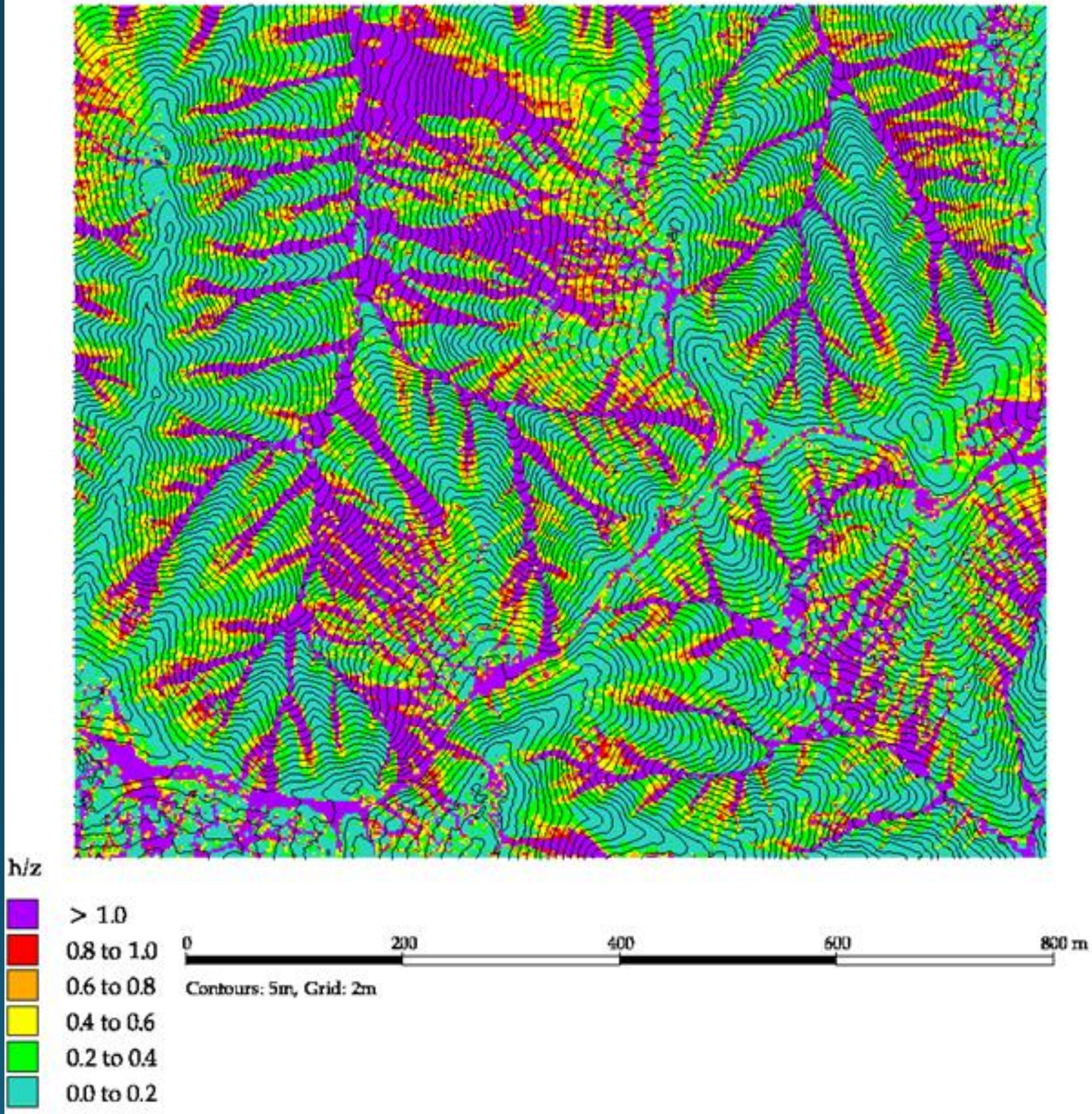


Figure 9.

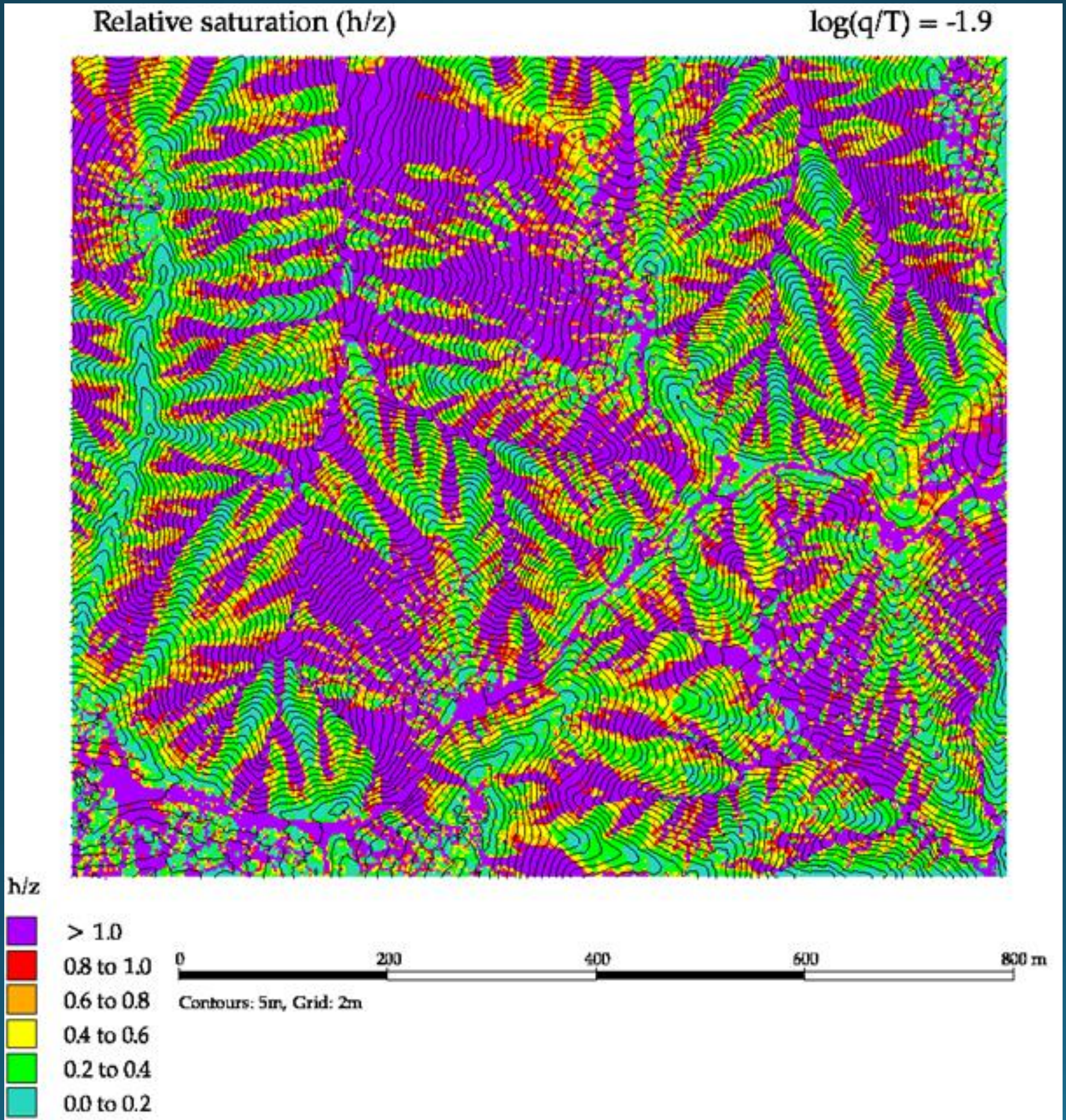

Relative saturation (h/z)
log(q/T) = -1.9
h/z
> 1.0
0.8 to 1.0
0.6 to 0.8
0.4 to 0.6
0.2 to 0.4
0.0 to 0.2
0
200
400
600
800 m
Contours: 5m, Grid: 2m

Figure 9.

Coupled hydrologic and slope stability model: SHALSTAB

- The slope stability model (Eq. 2) and the hydrologic model (Eq.5) can be combined and can be solved for either the hydrologic ratio:

$$\frac{q}{T} = \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right)\frac{b}{a}\sin\theta \qquad (6a)$$

- or the area per outflow boundary length

$$\frac{a}{b} = \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right)\frac{T}{q}\sin\theta \qquad (6b)$$

- Eq.6 is the coupled hydrologic-slope stability equation solved by SHALSTAB.
- The model has three topographic terms that are defined by the numerical surface used in the digital terrain model: drainage area, a, outflow boundary length, b, and hillslope angle, q.
- There are potentially four parameters that need to be assigned to apply this model: the soil bulk density, r_s, the angle of internal friction, f, the soil transmissivity, T, and the effective precipitation, q.
- It was observed that it useful to assign bulk density and friction angle values to be the same everywhere, and compare q/T values, making Eq. (6) a parameter free model.
- Although Eq.(6) can be reduced to a parameter free condition, it is still dimensional. The ratio of q/T is equal to length/time over length squared per time, i.e. it has the dimensions of 1/length. Using the metric system, and the unit of q/T will be 1/meters or for T/q it is meters. Likewise, the dimension of a/b is meters.
- Following figures shows the progress of unstable regions progressively expands up the valleys and eventually across the slope as T/q lowers (or as log(q/T) increases), simulating the effect of progressively larger storms.

$\log(q/T) = -3.1$

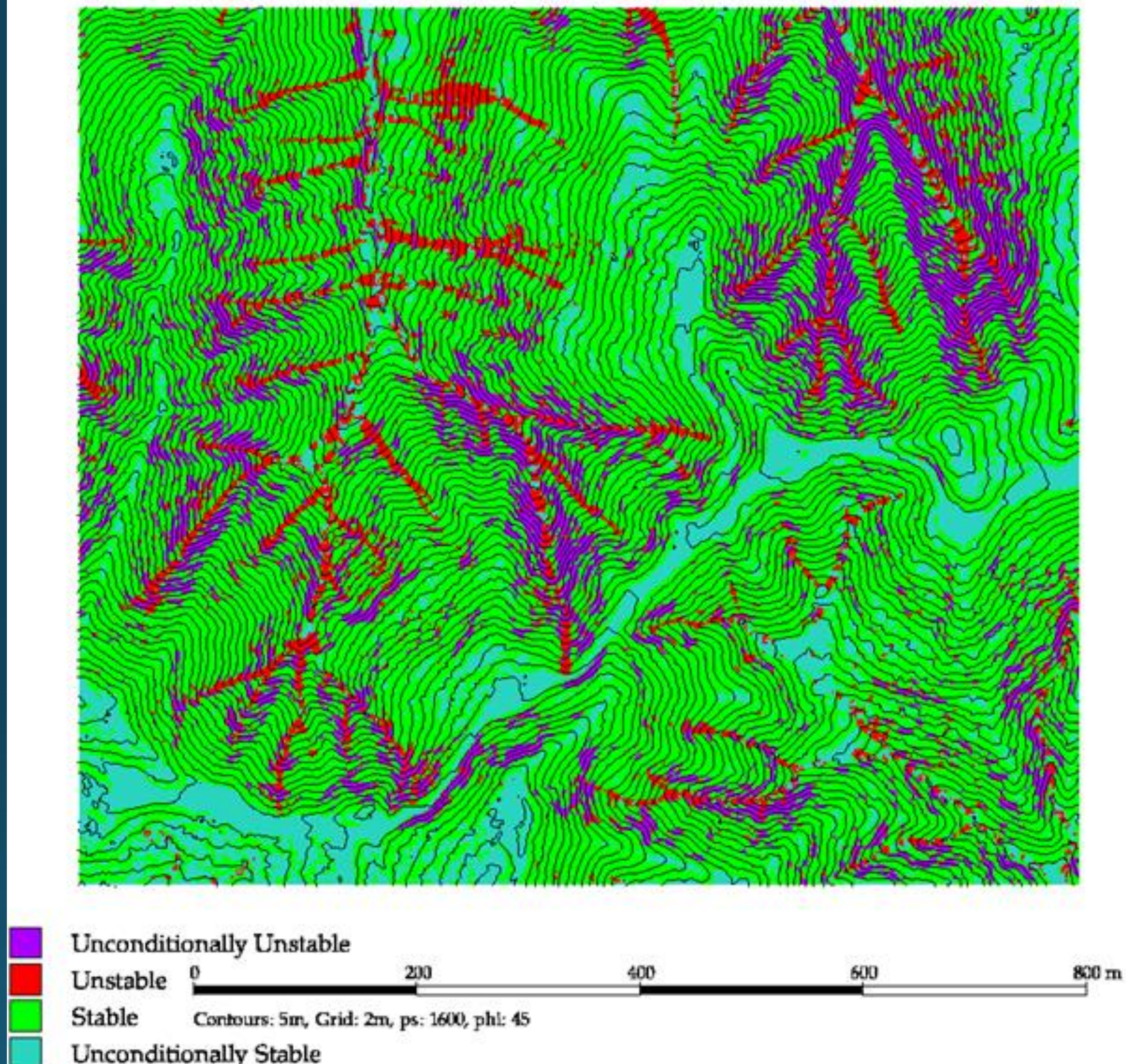


Figure 10.

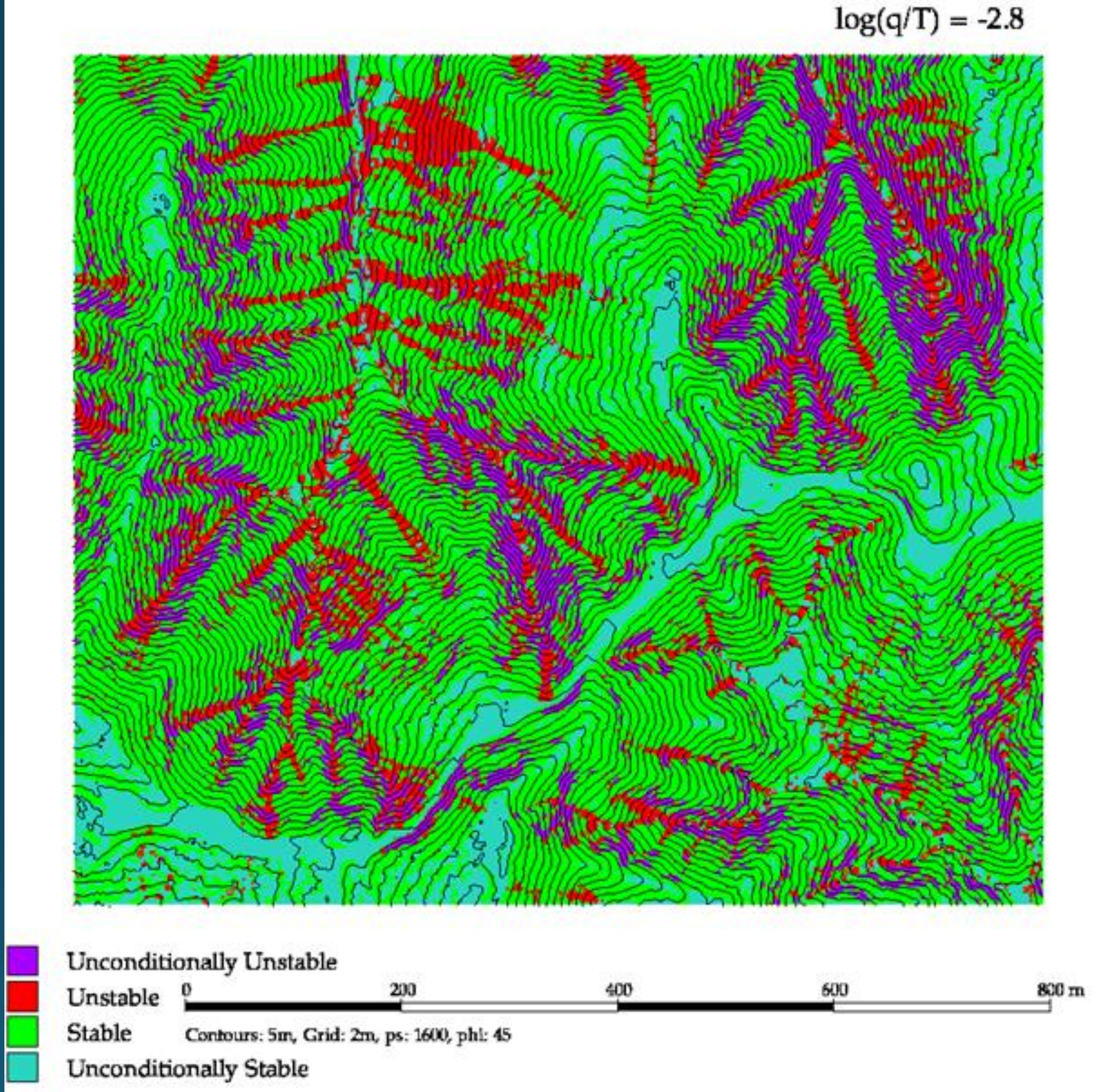

log(q/T) = -2.8
Unconditionally Unstable
Unstable
Stable
Unconditionally Stable
0
200
400
600
800 m
Contours: 5m, Grid: 2m, ps: 1600, phi: 45

Figure 10.

$\log(q/T) = -1.9$

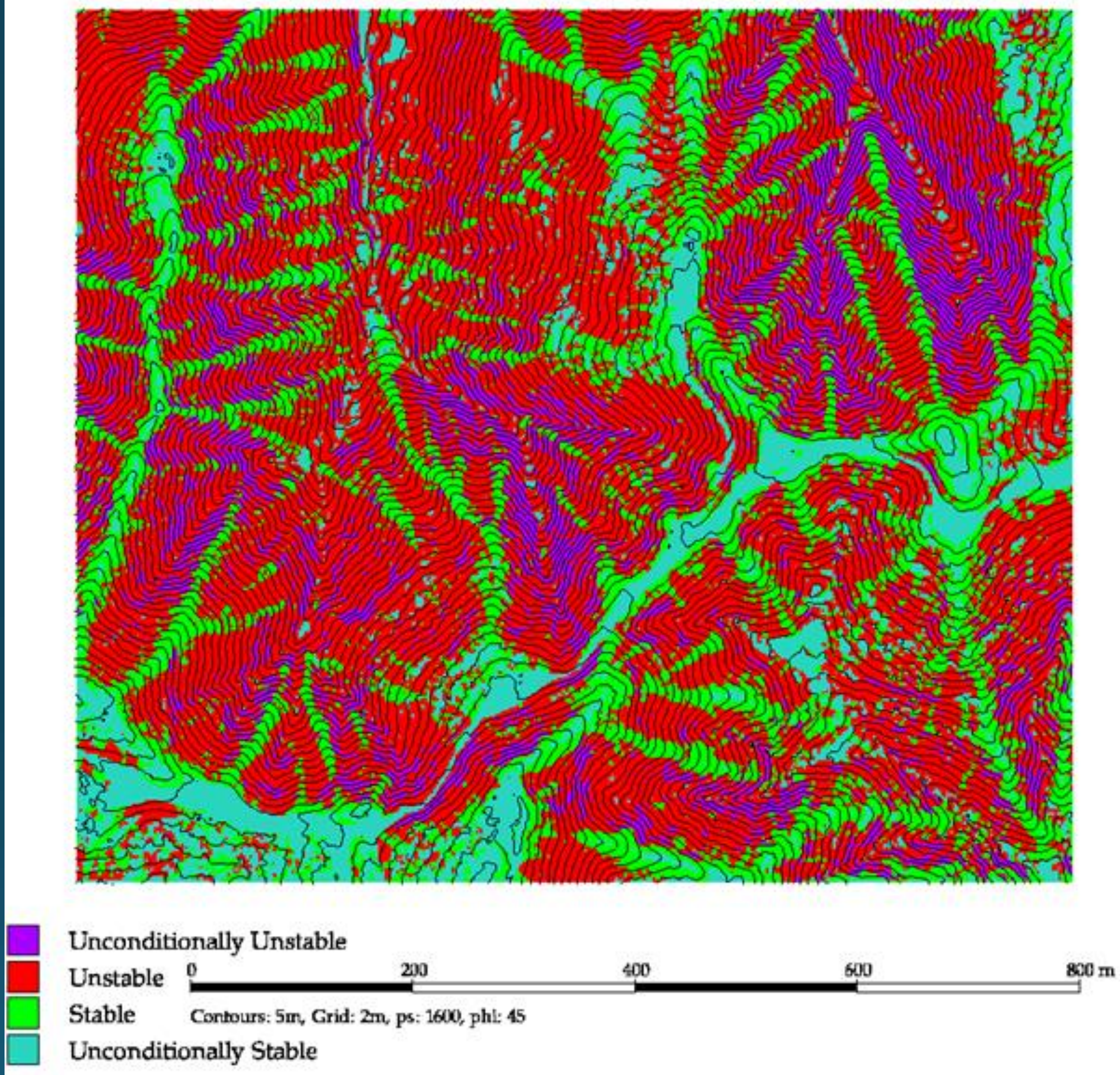
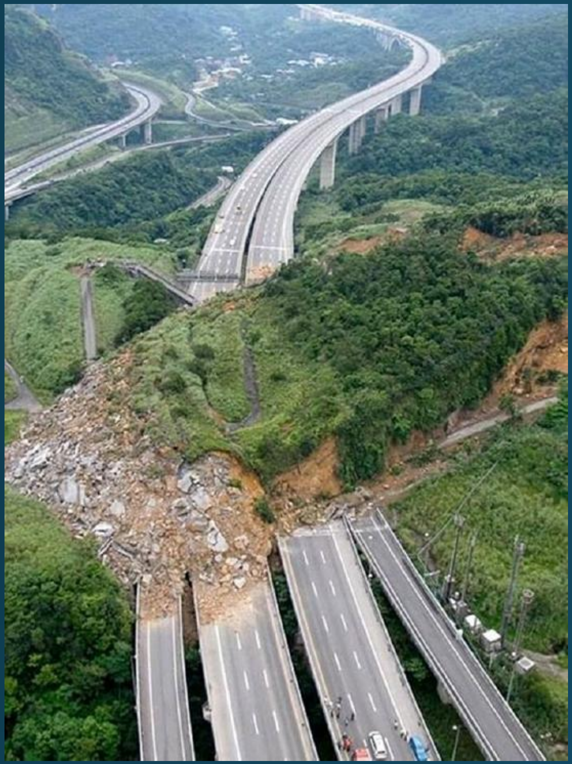


Figure 10.

- SHALSTAB is a physically-based digital terrain model for mapping the relative shallow slope stability potential across a landscape.
- Extensive testing of the model and application in practical contexts suggest that the model can be successfully used to delineate observed landslide scar locations and provides an objective procedure for delineating future potential sites of instability.
- It can be used as a parameter free model in which the only decision is how to rank the mapped pattern of relative stability into such categories as "high", "medium" and "low" for the practical purpose of prescribing some land management practice.
- This utility is accomplished by eliminating many processes or factors that do matter to slope instability but require too much local parameterization to be useful in a practical context for application over large areas. Hence, this model only routes water through the landscape at steady state, rather than dynamically modeling storm events.
- It is the underlying hypothesis here, seemingly well supported with observation, that the overriding influence of topography on the local evolution of a perched water table, permits the steady state model to emulate the effects of dynamic storm response.
- This is not to say that dynamic modeling of landscape response to storms is not a valuable enterprise.



Torrential rains poured down on El Salvador in early November, triggering massive flooding and landslides.