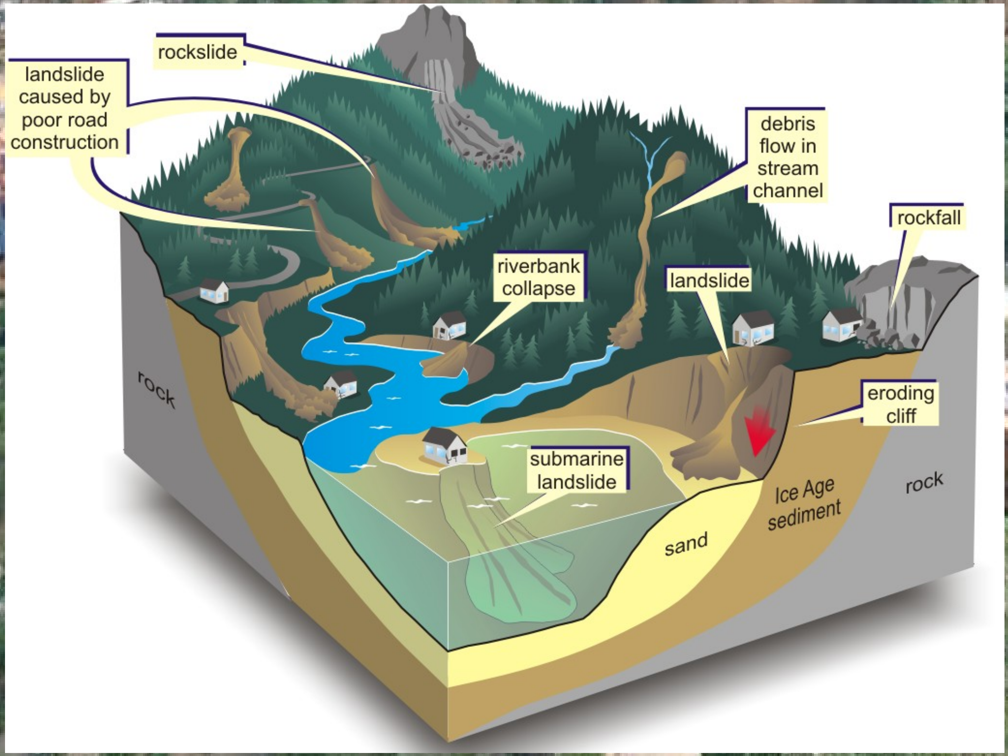
Causes and triggers of shallow landslides

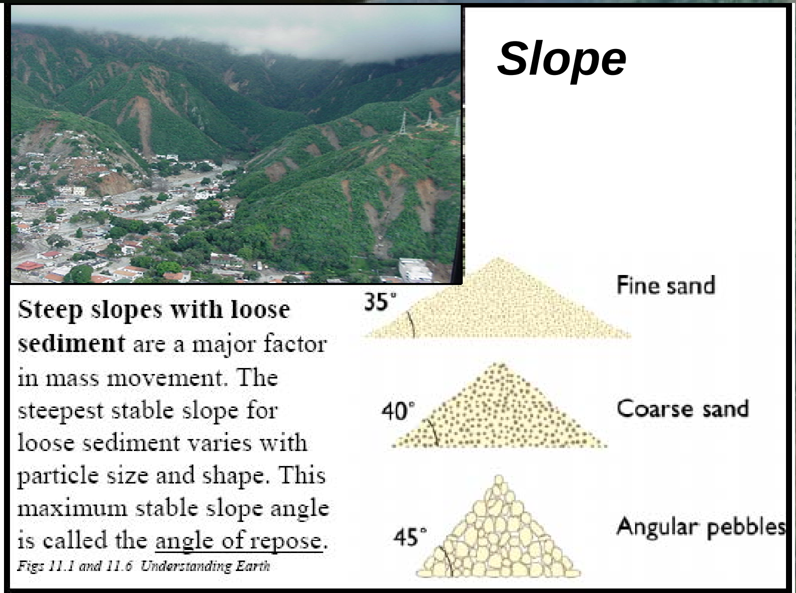
Maria Cristina Rulli, Daniele Bocchiola, Renzo Rosso

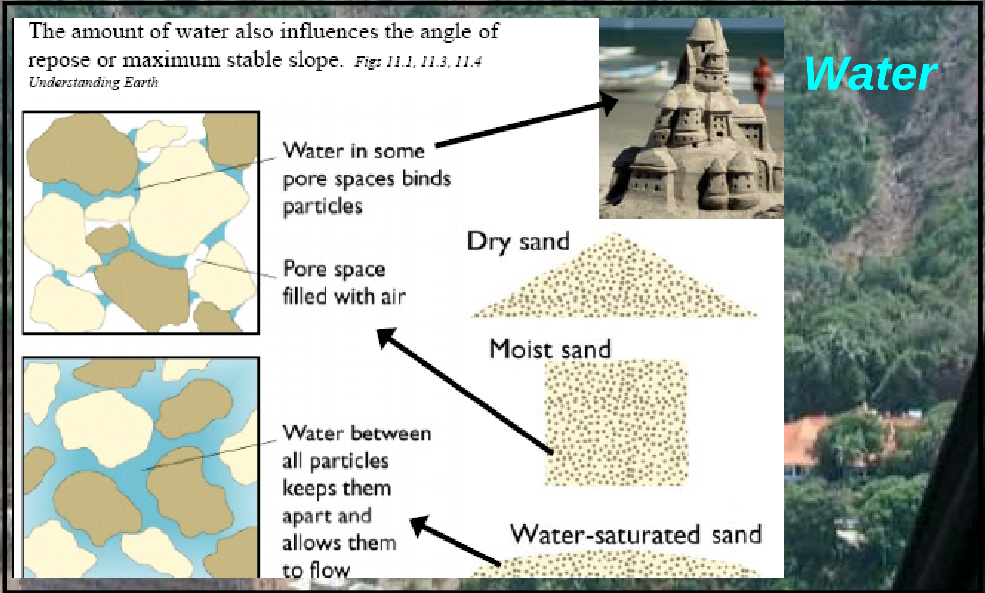
Politecnico di Milano

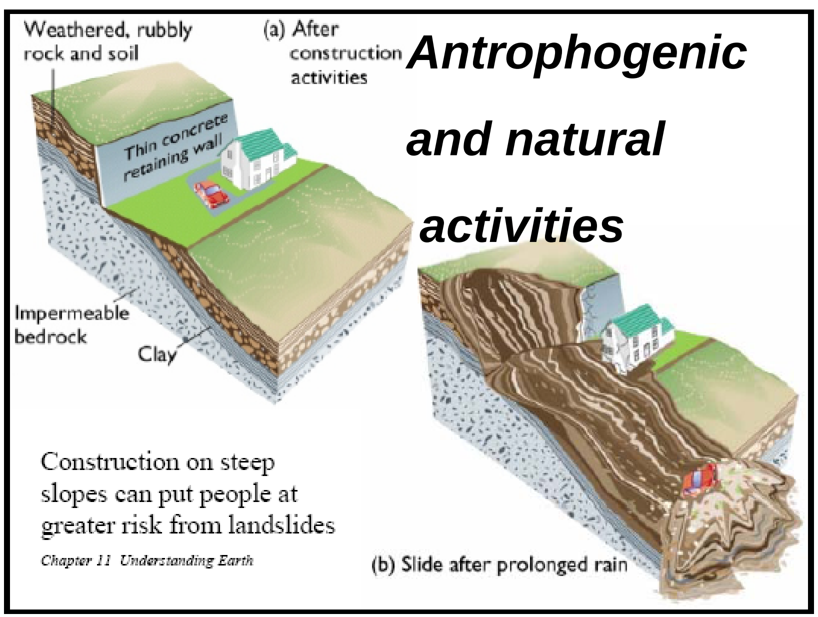
cristina.rulli@polimi.it



Factors which influence or trigger mass movement



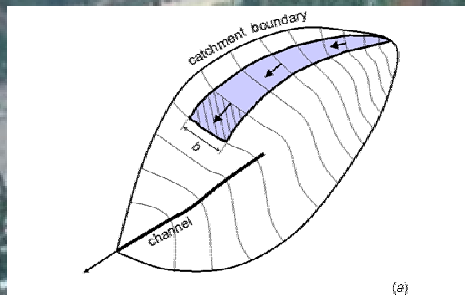


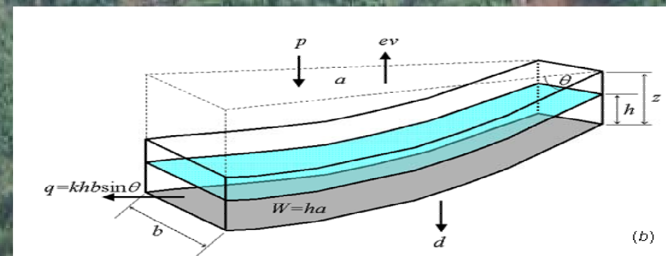


Photograph of a typical burned hillslope in southern California. Photograph by Sue Cannon.

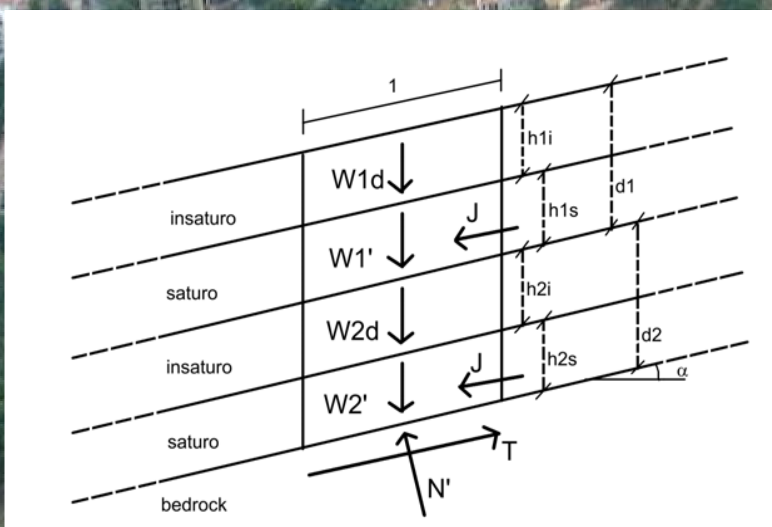
Precipitation induced landslides at basin scale

The problem is usually solved in term of SF by coupling an hydrological model with a geomechanical model





Rosso R, Rulli M.C. Vannucchi G., WRR 2006



$$Fs = \frac{c_A + c_v + c_1 + \left[z \cdot \gamma_{d1} \cdot \cos^2\alpha + W\cos\alpha\right] \cdot \tan\phi_1}{\left(z \cdot \gamma_{d1} \cdot \cos\alpha + W\right) \cdot sen\alpha} \qquad 0 < z < h_{i1}$$

$$Fs = \frac{c_1 + c_v + \left\{\left[h_{i1} \cdot \gamma_{d1} + (z - h_{i1}) \cdot (\gamma_{sat1} - \gamma_w)\right] \cdot \cos^2\alpha + W \cdot \cos\alpha\right\} \cdot \tan\phi_1}{\left[h_{i1} \cdot \gamma_{d1} + (z - h_{i1}) \cdot \gamma_{sat1}\right] \cdot sen\alpha \cdot \cos\alpha + W \cdot sen\alpha} \qquad h_{i1} < z < d_1$$

$$Fs = \frac{\min(c_1, c_2) + \left\{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot (\gamma_{sat1} - \gamma_w)\right] \cdot \cos^2\alpha + W \cdot \cos\alpha\right\} \cdot \tan(\min(\phi_1, \phi_2))}{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot \gamma_{sat1}\right] \cdot sen\alpha \cdot \cos\alpha + W \cdot sen\alpha} \qquad z = d_1$$

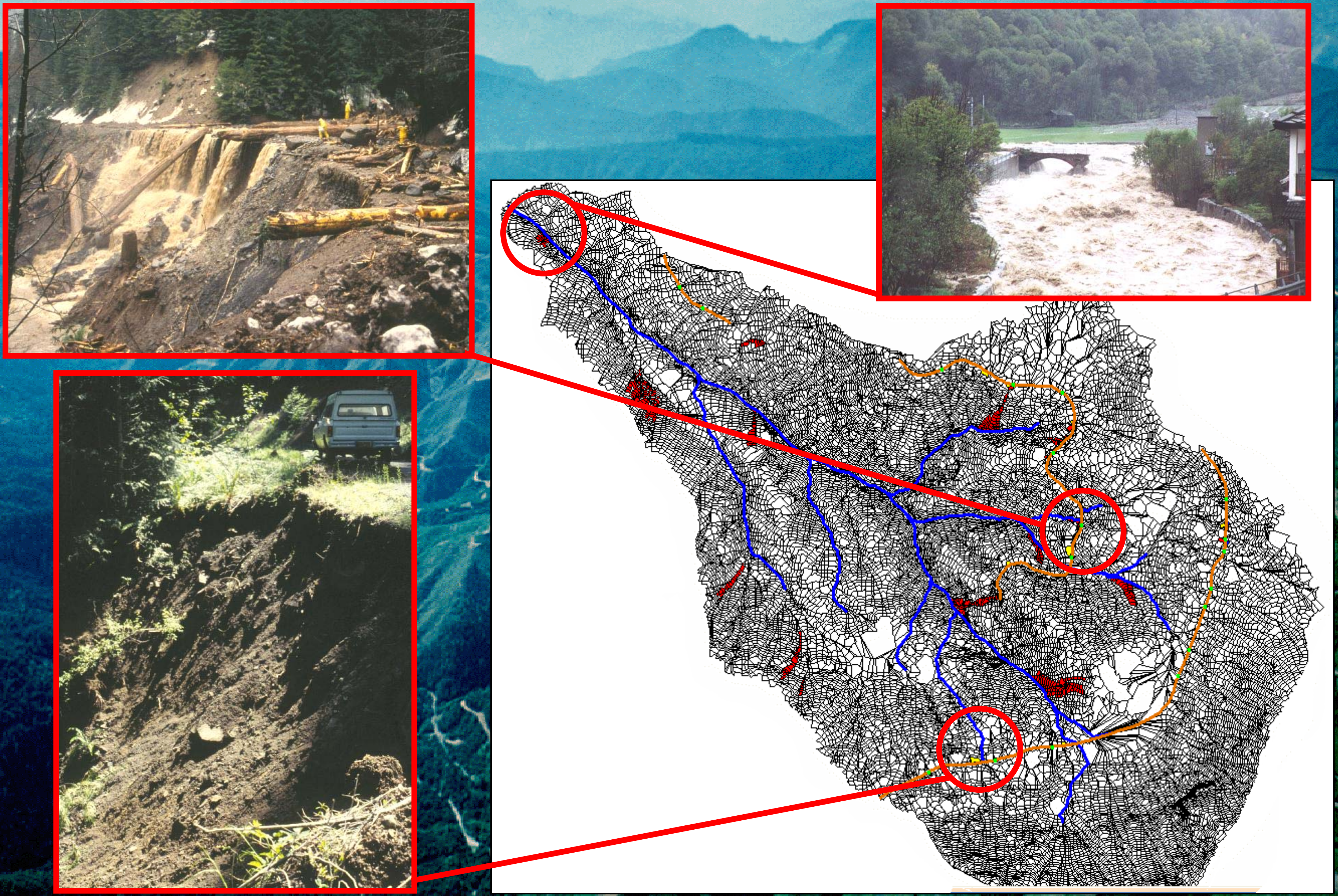
$$Fs = \frac{c_A + c_2 + \left\{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot (\gamma_{sat1} - \gamma_w) + (z - d_1) \cdot \gamma_{d2}\right] \cdot \cos^2\alpha + W \cdot \cos\alpha\right\} \cdot \tan\phi_2}{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot \gamma_{sat1} + (z - d_1) \cdot \gamma_{d2}\right] \cdot sen\alpha \cdot \cos\alpha + W \cdot sen\alpha} \qquad d_1 < z < d_1 + h_{i2}$$

$$Fs = \frac{c_2 + \left\{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot (\gamma_{sat1} - \gamma_w) + h_{i2} \cdot \gamma_{d2} + (z - d_1 - h_{i2}) \cdot (\gamma_{sat2} - \gamma_w)\right] \cdot \cos^2\alpha + W \cdot \cos\alpha\right\} \cdot \tan\phi_2}{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot \gamma_{sat1} + h_{i2} \cdot \gamma_{d2} + (z - d_1 - h_{i2}) \cdot \gamma_{sat2}\right] \cdot sen\alpha \cdot \cos\alpha + W \cdot sen\alpha}$$

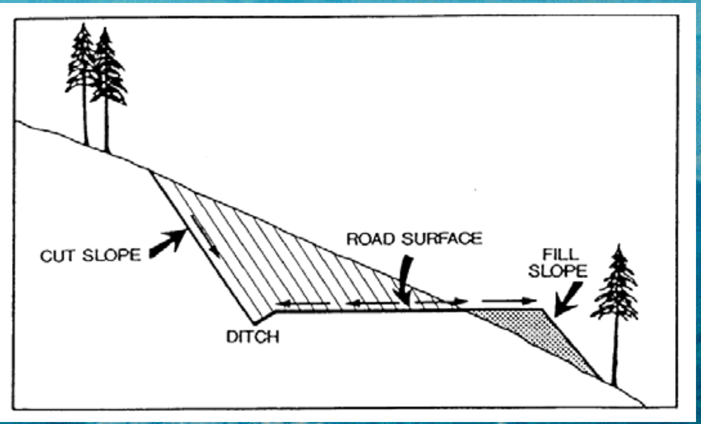
$$d_1 + h_{i2} < z < d_1 + d_2$$

$$Fs = \frac{\tan\phi_{br}}{\tan\alpha} \qquad z = d_1 + d_2$$

Roads effect on shallow landslides triggering



Hydrological Effects:



Roads Effects

- Road surface and Ditches → Increase Overland Flow
- Road Cut → Intercept Subsurface Flow
- Culverts → Add new Channel to stream network

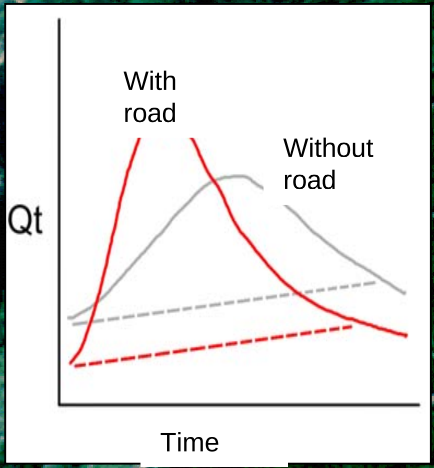
Channel Network Extension

Increase quick discharge

Increase and anticipation of peak discharge → **Volumetric and Timing Effect**

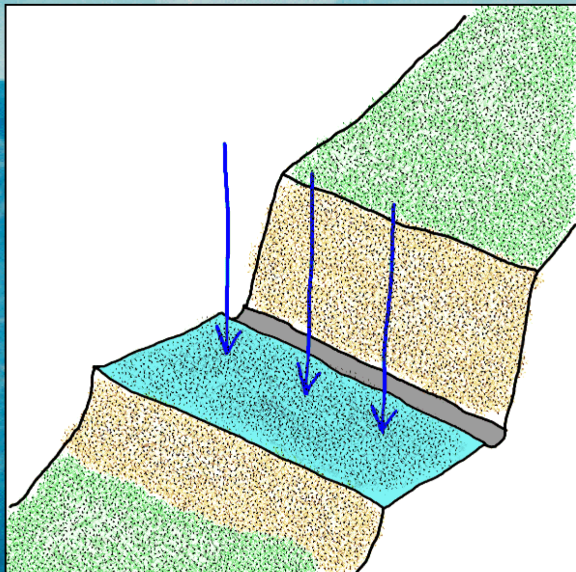
$$Q(t) = Q_{base} + Q_{quick}$$

$$\Delta Q_{quick} = \begin{cases} Q_{rain} \\ Q_{cutroad} \end{cases}$$



(From Wemple, et al. 1996)

Flow Interception by the ROAD



Rainfall Effect on the road

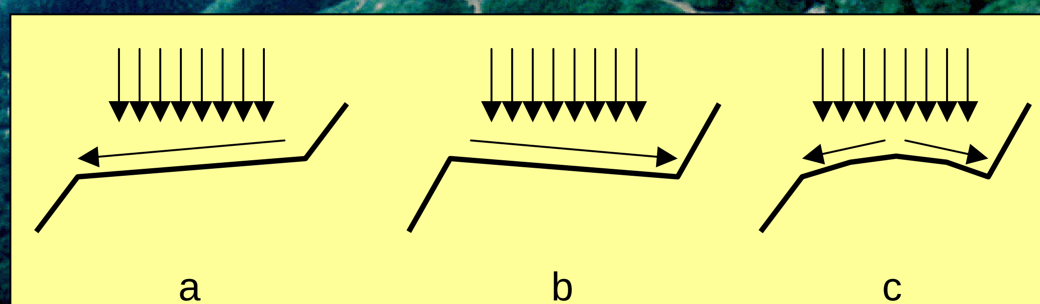
Hp: Impervious Road Surface
Small roughness
Negligible vegetation transpiration and interception

Hydraulic Analogy: Road - Channel

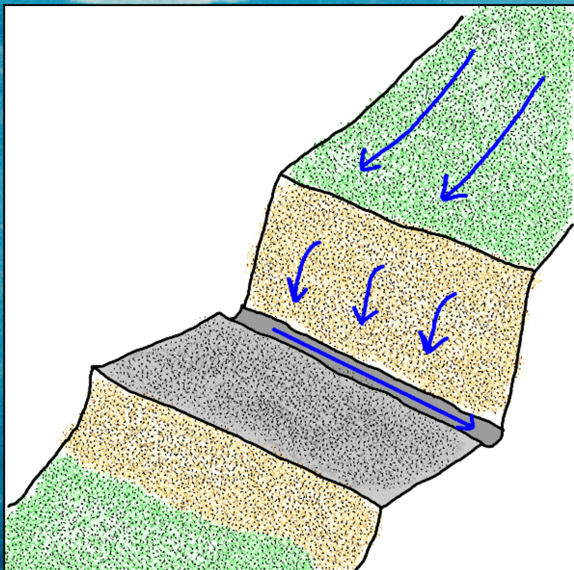
$$Q_{rain} = I_r \cdot A_{road}$$

a. Outsloped
b. Insloped
c. Crowned

Runoff generation on the road and on the ditch



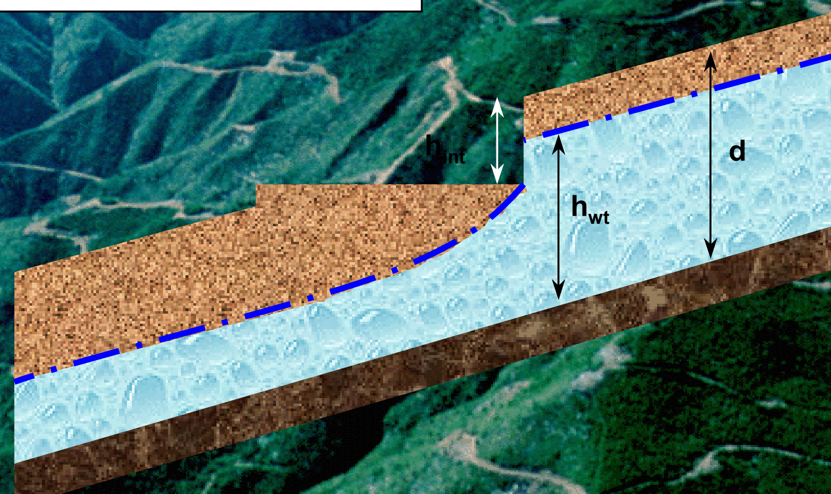
Flow Interception by the ROAD



Effect of the road cut

Overland and Subsurface Flow interception

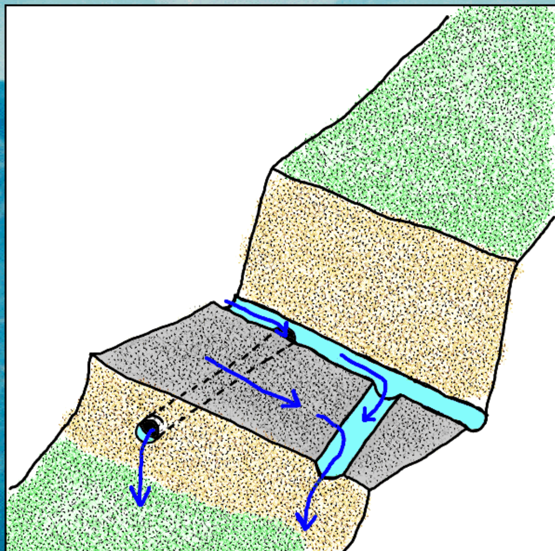
$$Q_{roadcut} = Q_{overland} + Q_{subsurface}$$



$$Q_{subsurface \rightarrow Overland\text{-}road} \propto \frac{h_{int} - (d - h_{wt})}{h_{wt}}$$

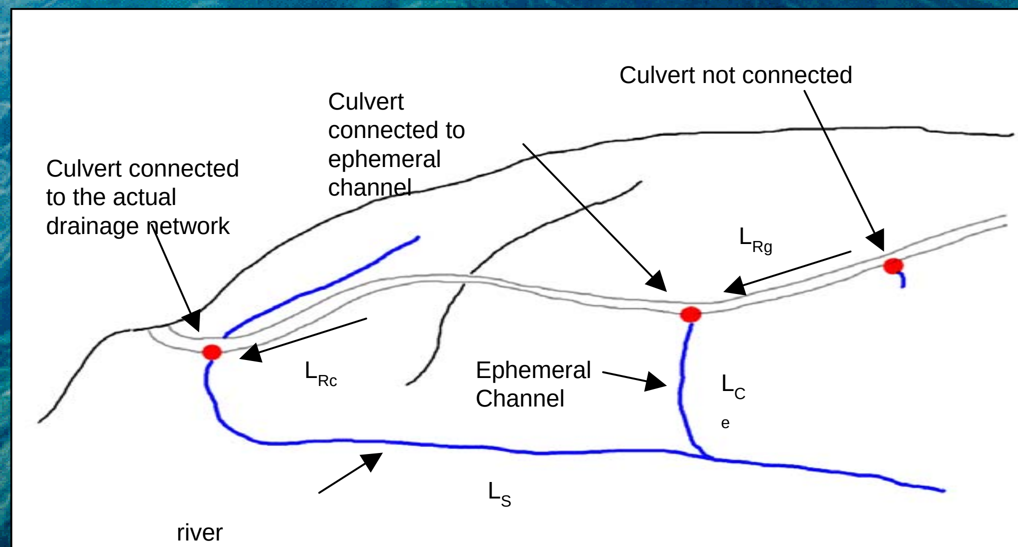
$$Q_{subsurface \rightarrow subsurfacde} \propto \frac{(d - h_{int})}{h_{wt}}$$

Flow Interception by the ROAD



The intercepted discharge by the road is routed downslope trough the culvets

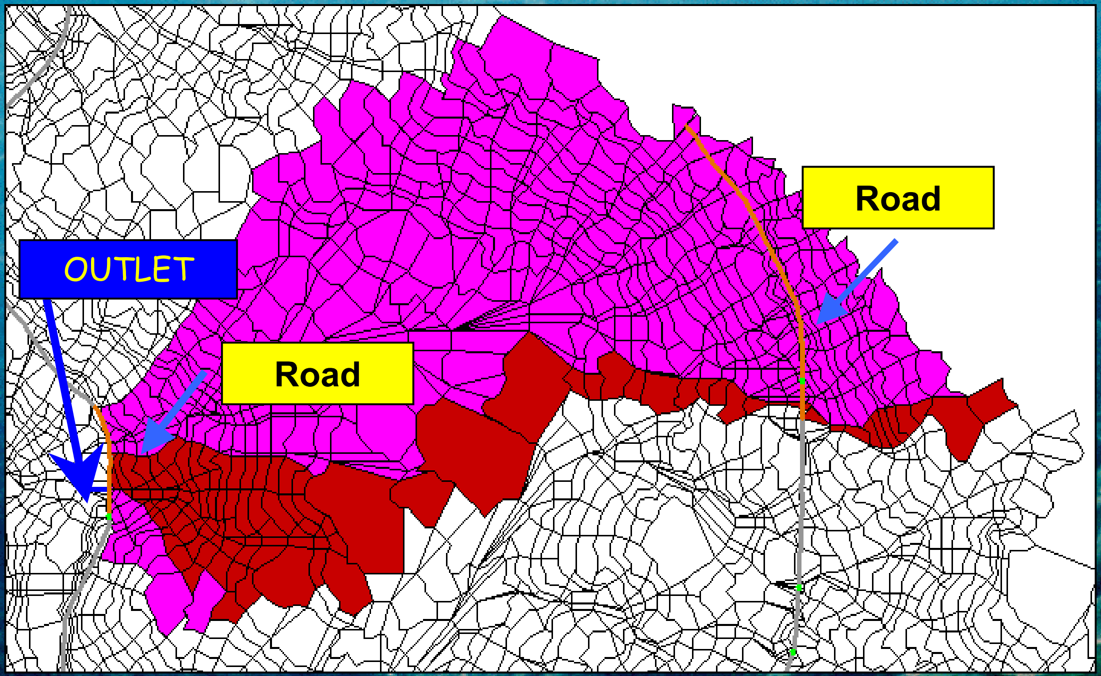
Drainage paths Changes



Drainage Density

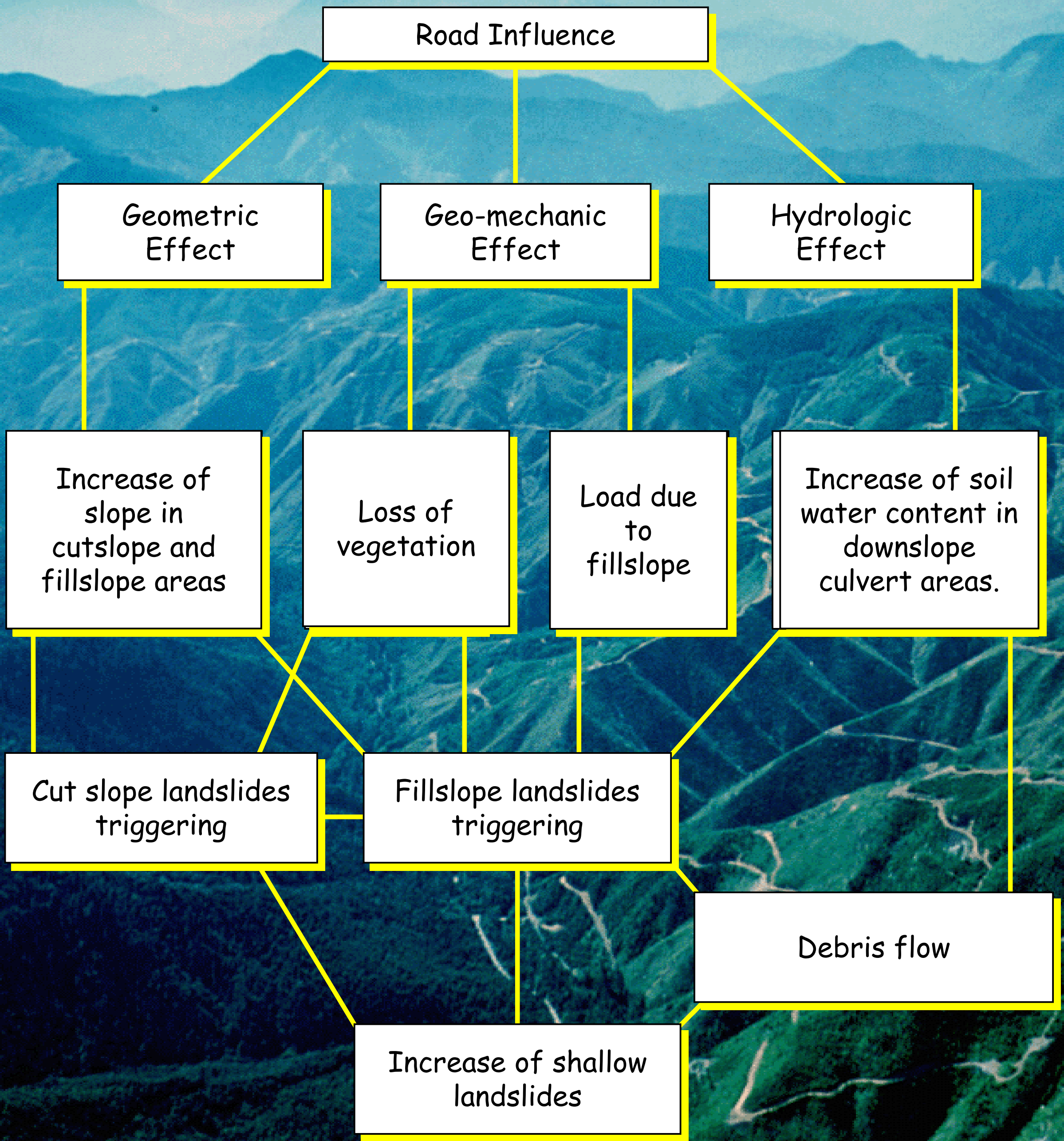
$$D_d = \frac{\sum L_S}{A}$$

$$D'_d = \frac{\sum \left(L_S + L_{Rc} + L_{Rg} + L_{Ce} \right)}{A}$$



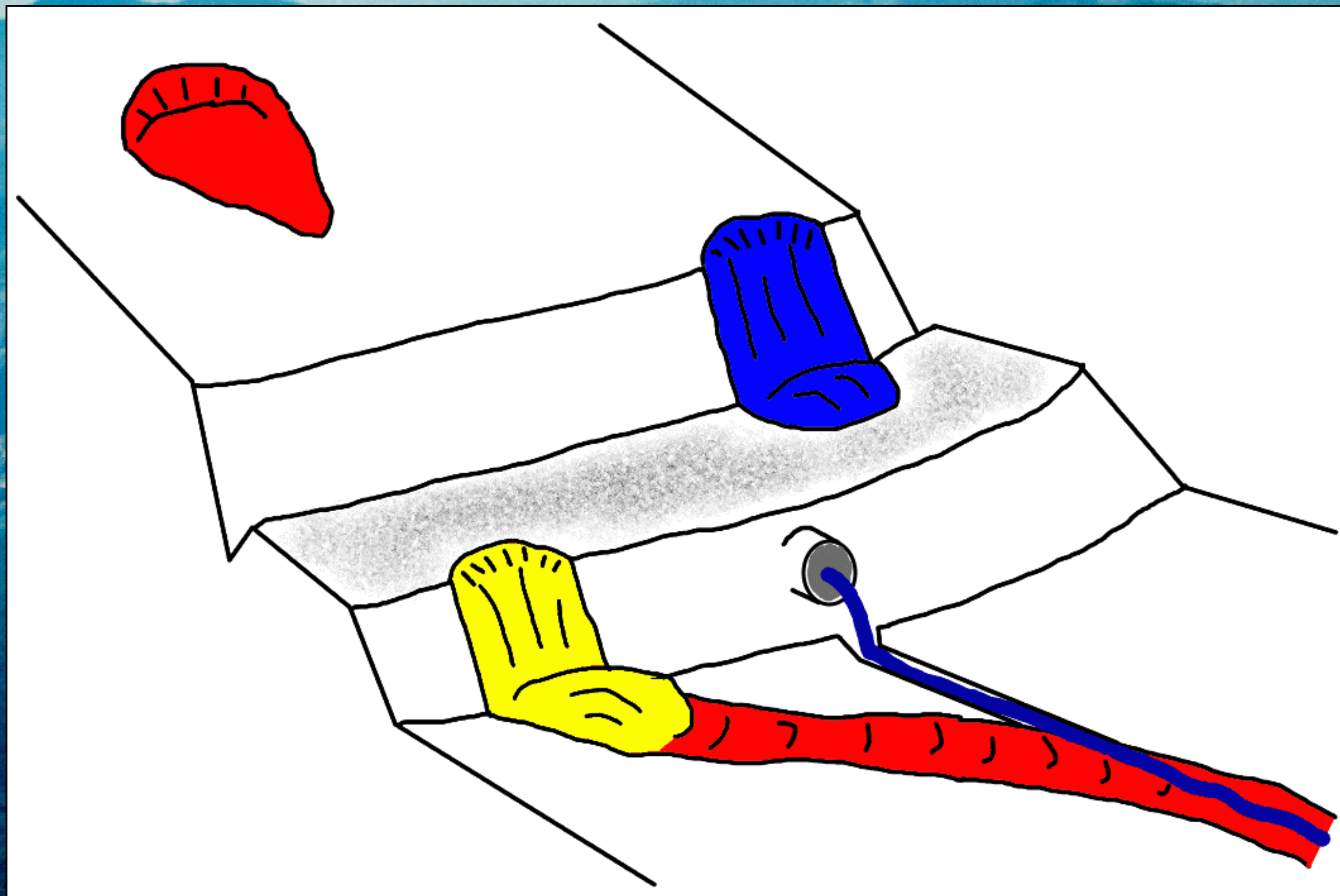
The presence of ROADS can modify contributing area at selected point

Geomechanical Effects:



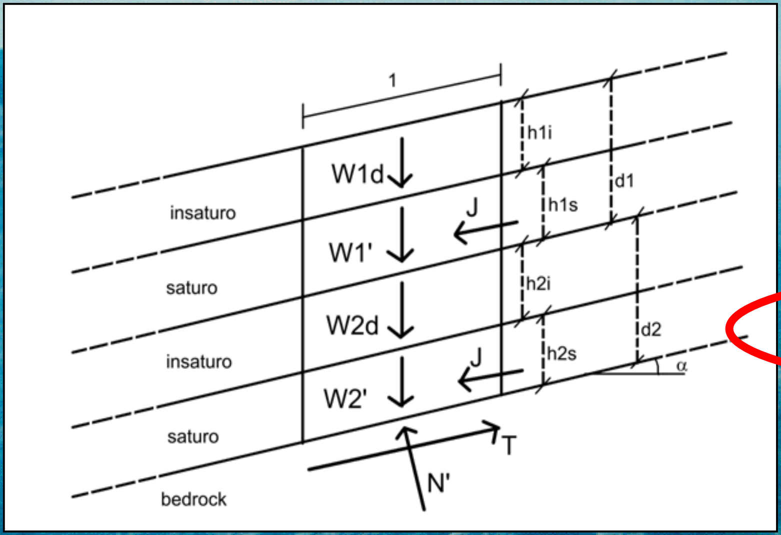
Debris flow are not taken in account in the present analysis

Shallow landslides typology



Hillslope Slides
(infinite slope analysis)
Cutslope Slides
(Stability maps)
Fillslope Slides
(Stability maps)

Hillslope SLIDES Infinite Slope Analysis



$$Fs = \frac{c_A + c_v + c_1 + \left[z \cdot \gamma_{d1} \cdot \cos^2\alpha + W\cos\alpha\right] \cdot \tan\phi_1}{\left(z \cdot \gamma_{d1} \cdot \cos\alpha + W\right) \cdot sen\alpha}$$ $0 < z < h_{i1}$

$$Fs = \frac{c_1 + c_v + \left\{\left[h_{i1} \cdot \gamma_{d1} + (z - h_{i1}) \cdot (\gamma_{sat1} - \gamma_w)\right] \cdot \cos^2\alpha + W \cdot \cos\alpha\right\} \cdot \tan\phi_1}{\left[h_{i1} \cdot \gamma_{d1} + (z - h_{i1}) \cdot \gamma_{sat1}\right] \cdot sen\alpha \cdot \cos\alpha + W \cdot sen\alpha}$$ $h_{i1} < z < d_1$

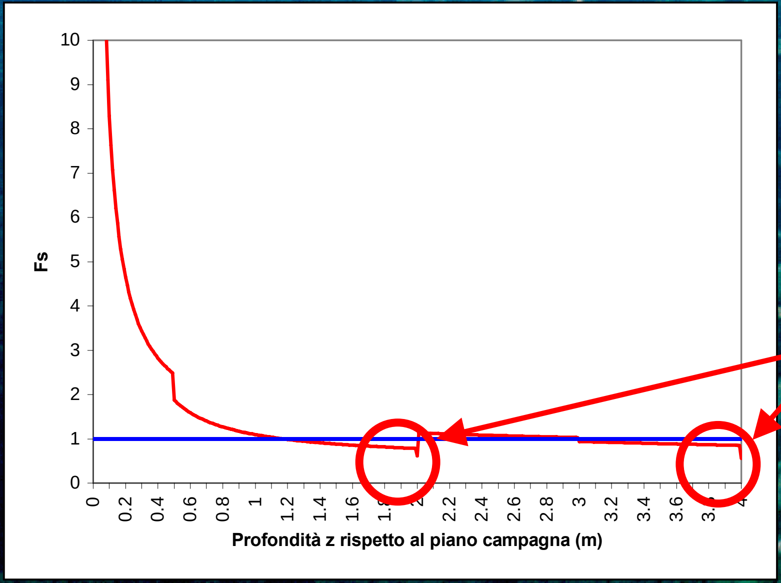
$$Fs = \frac{\min(c_1, c_2) + \left\{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot (\gamma_{sat1} - \gamma_w)\right] \cdot \cos^2\alpha + W \cdot \cos\alpha\right\} \cdot \tan(\min(\phi_1, \phi_2))}{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot \gamma_{sat1}\right] \cdot sen\alpha \cdot \cos\alpha + W \cdot sen\alpha}$$ $z = d_1$

$$Fs = \frac{c_A + c_2 + \left\{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot (\gamma_{sat1} - \gamma_w) + (z - d_1) \cdot \gamma_{d2}\right] \cdot \cos^2\alpha + W \cdot \cos\alpha\right\} \cdot \tan\phi_2}{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot \gamma_{sat1} + (z - d_1) \cdot \gamma_{d2}\right] \cdot sen\alpha \cdot \cos\alpha + W \cdot sen\alpha}$$ $d_1 < z < d_1 + h_{i2}$

$$Fs = \frac{c_2 + \left\{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot (\gamma_{sat1} - \gamma_w) + h_{i2} \cdot \gamma_{d2} + (z - d_1 - h_{i2}) \cdot (\gamma_{sat2} - \gamma_w)\right] \cdot \cos^2\alpha + W \cdot \cos\alpha\right\} \cdot \tan\phi_2}{\left[h_{i1} \cdot \gamma_{d1} + h_{S1} \cdot \gamma_{sat1} + h_{i2} \cdot \gamma_{d2} + (z - d_1 - h_{i2}) \cdot \gamma_{sat2}\right] \cdot sen\alpha \cdot \cos\alpha + W \cdot sen\alpha}$$

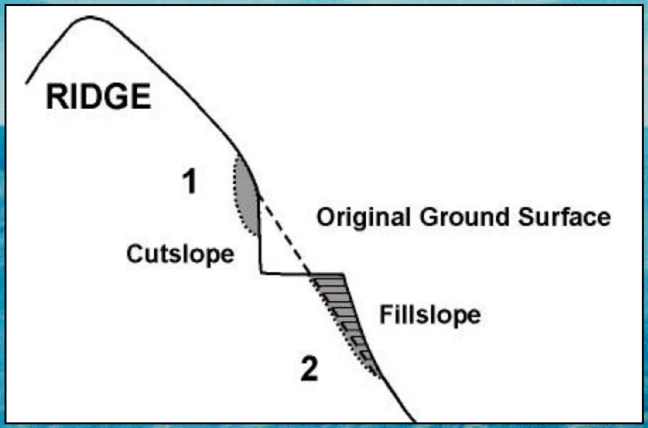
$d_1 + h_{i2} < z < d_1 + d_2$

$$Fs = \frac{\tan\phi_{br}}{\tan\alpha}$$ $z = d_1 + d_2$



most probable sliding surfaces

Cutslope and Fillslope SLIDES: Stability Charts analysis



- Hypothesis:
  - Circular failure surface
  - hillslope simple geometry
  - Soil having friction and cohesion
  - Soil homogeneous and isotropic

  Friction circle method

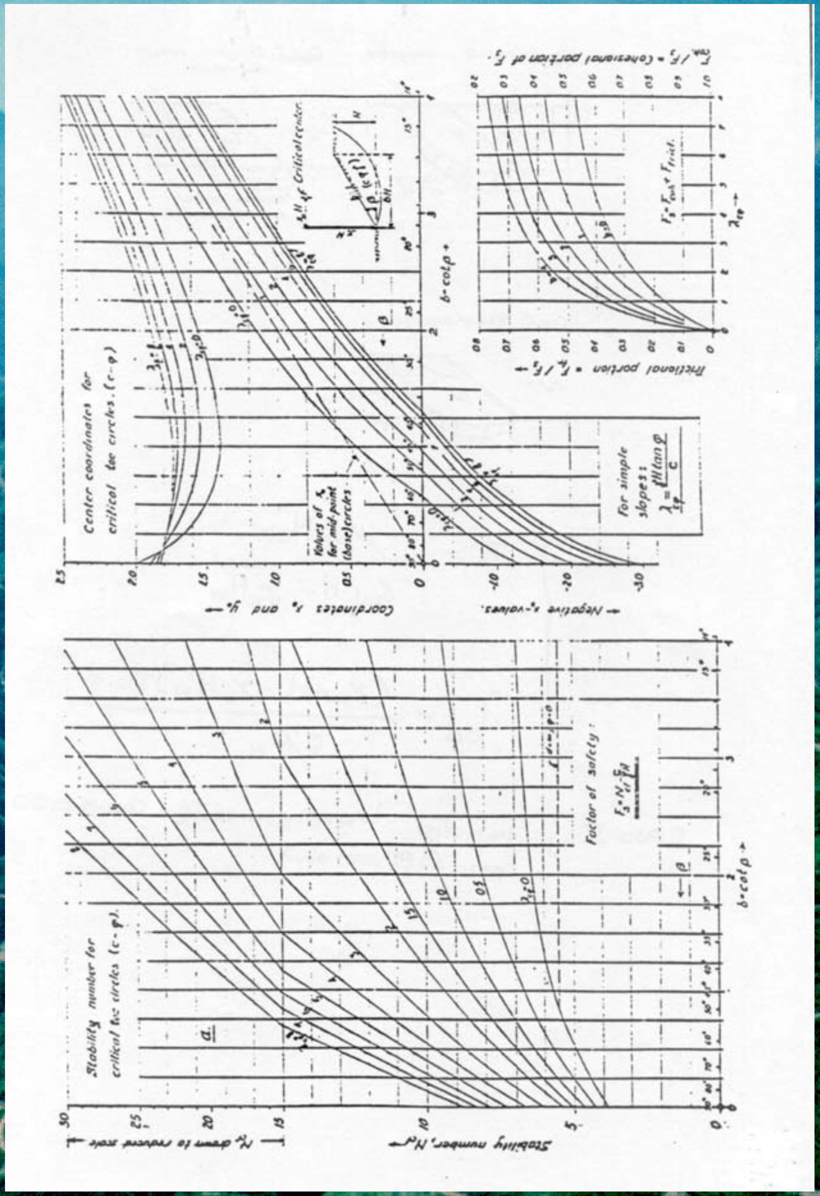
- Mohr-Coulomb: $\tau = c' + \sigma' \tan \phi'$

- Safety Factor: $$F_S = \frac{N_{CF}\, c'}{P_d}$$

with $\lambda_{C\phi} = \frac{P_e tg\,\phi'}{c'}$ and $N = \frac{c}{\gamma H}$

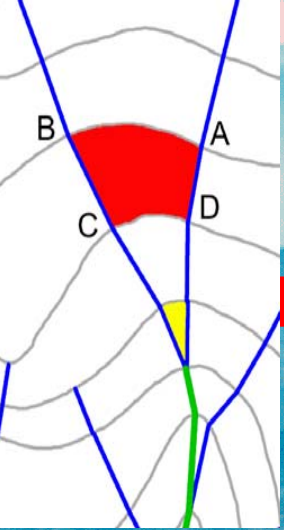
$$P_e = \frac{\gamma H + q - \gamma_W H'_W}{\mu_q \mu'_W}$$

$$P_d = \frac{\gamma H + q - \gamma_W H_W}{\mu_q \mu_W \mu_t}$$



Taylor, 1948

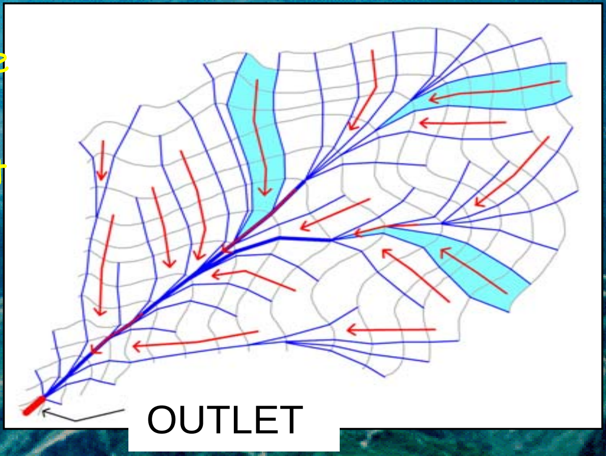
BASIN PARTITIONING: state of the art



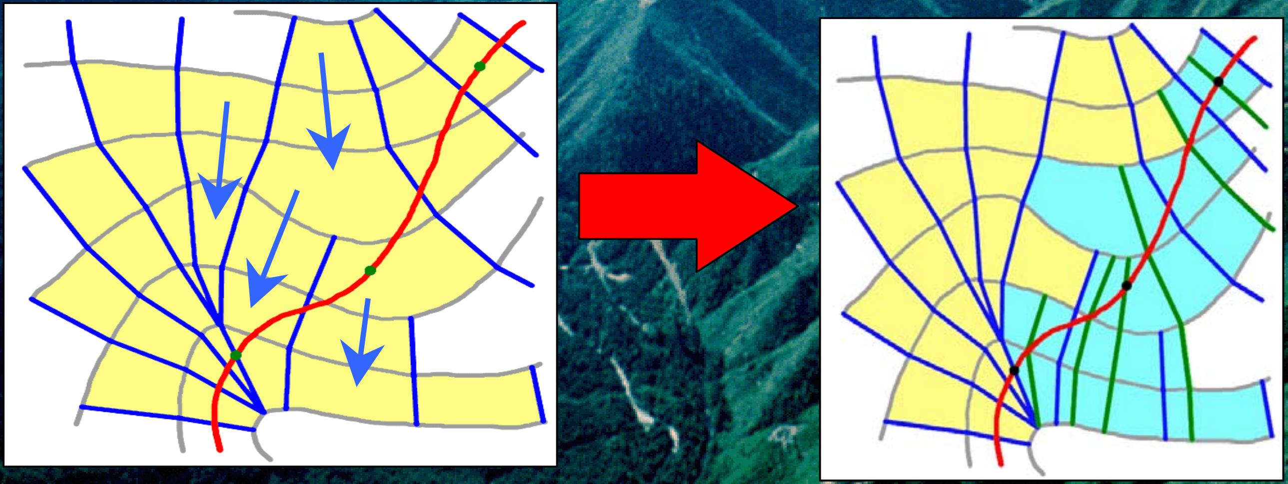
The model is a contour-based model. It derives at first the drainage network starting from the highest contour, then proceeds downslopes follow the steepest lines (Menduni et al., 2000). Two type of topographic elements are considered in flow accounting and routing:

Cell : polygon having two vertexes on two adjacent contours and two vertexes on two steepest lines. It can be triangular when 2 steepest lines meet.

Channel: mono-dimensional topographic element starting at the junction of 2 steepest lines



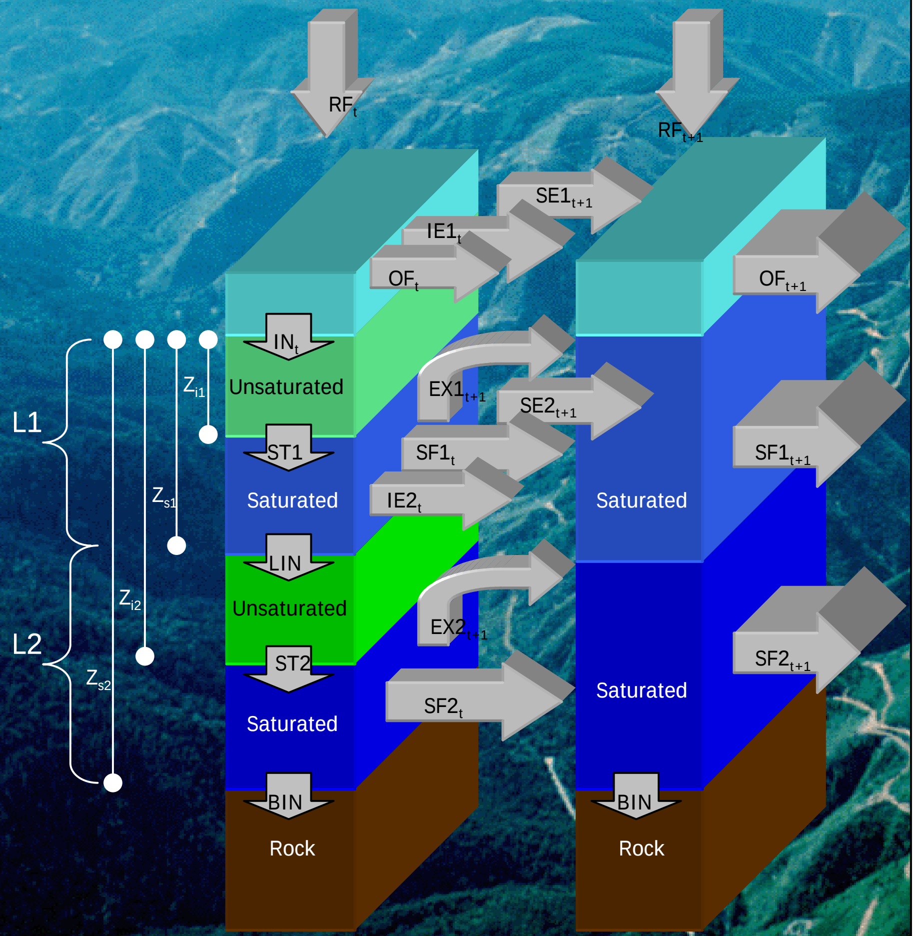
The effect of presence of ROAD on basin partitioning



Rulli M.C., Rosso R., 2008

Hydrological Fluxes

Simplified Bucket Model with Layers



- Saturated Hydraulic Conductivity:

$$K_S = K_0 e^{-fz} \quad \text{dove} \quad f = \frac{\theta_S - \theta_{dry}}{m}$$

- Water Content:

$$S = (z_s - z_i)\cdot(\theta_S - \theta_{dry}) \qquad I_d = (\theta_S - \theta_{dry})\cdot z_i - I_S$$

$$S_d = (\theta_S - \theta_{dry})\cdot z_s - S \qquad I_S = I - I_d$$

- Flux unsaturated -saturated:

$$st = K_S \frac{I_S}{S_d}$$

- Subsurface Flow:

$$sf = \tan(\alpha)\cdot K_S \cdot e^{\frac{-S_d}{m}}$$

- Infiltration:

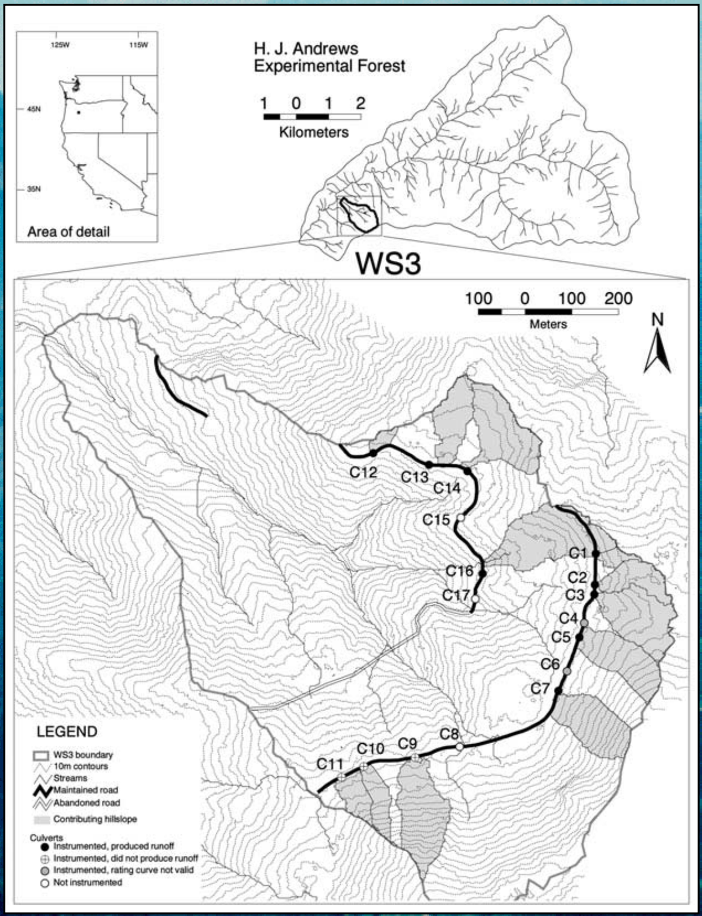
$$lin = K_i \frac{S_1}{I_{d2}}$$

- Percolation in the cracked Rock:

$$bin = K_{ar} \cdot \Delta t \quad \text{con} \quad K_{ar} = \frac{e}{b} K_f + K_m$$

Rulli M.C., Rosso R., AWR 2007

STUDY AREA

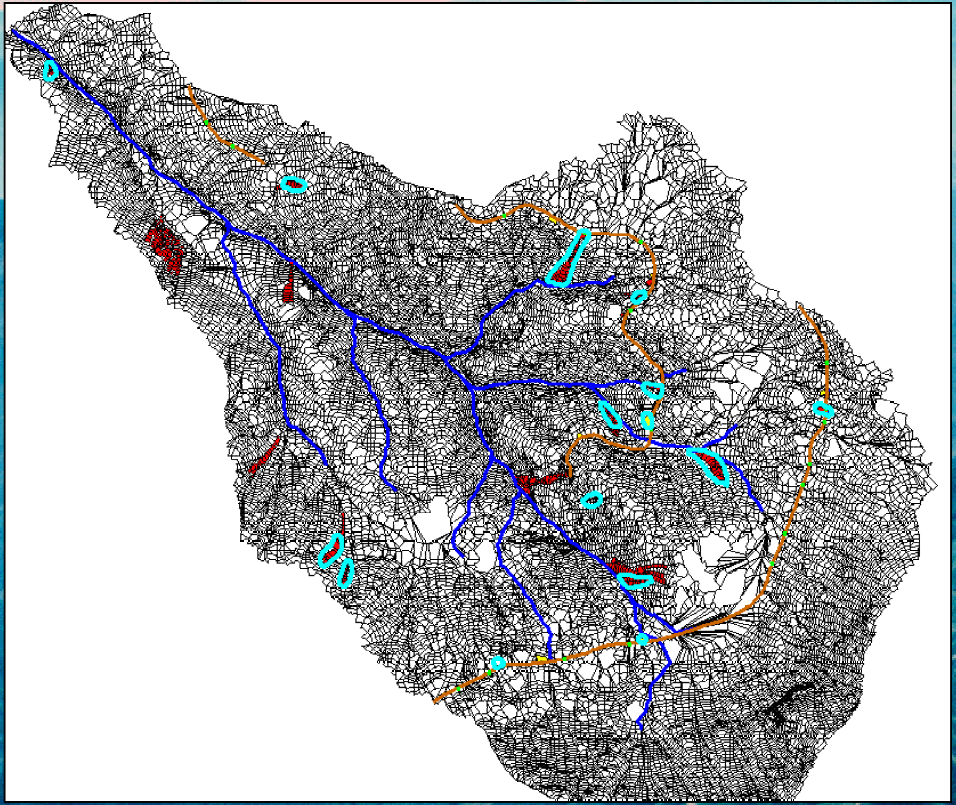


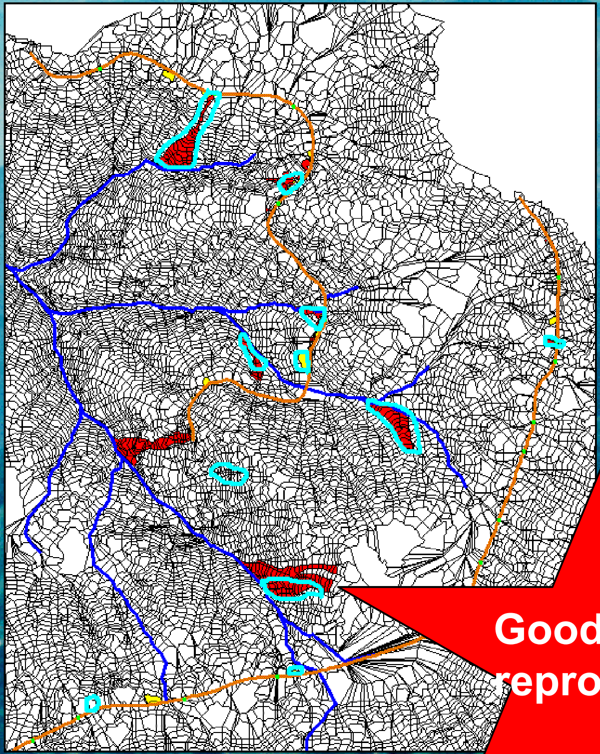
Study area is watershed 3 (WS3) at the H. J. Andrews Experimental Forest, Oregon. Location of roads, culverts, and instrumentation are shown.

- Elevation 470 – 1050 m a.s.l.
- Area 1 km^2
- Clay Soil
- Macropores in the soil
- Ks =$10^{-3} \div 10^{-5}$ m/s
- Mean Annual Precip. 2300 mm
- Mean rainfall Intensity 4 mm/h
- Mean Discharge $5*10^{-2}$ m^3/s
- In 1959 3 orders of roads were built.

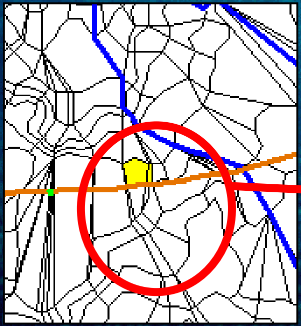
- Rainfall event
  3-9 February 1996:
  max rain 12 mm/h
  Total rain 340mm
- 16 shallow landslides:
  8 hillslope
  8 fillslope/cutslope

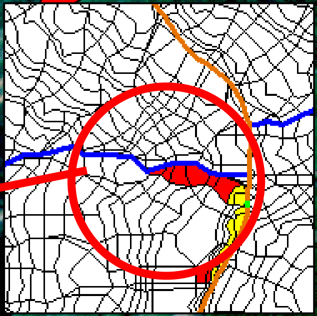
Rulli M.C., Rosso R., 2008





Good Model reproduction



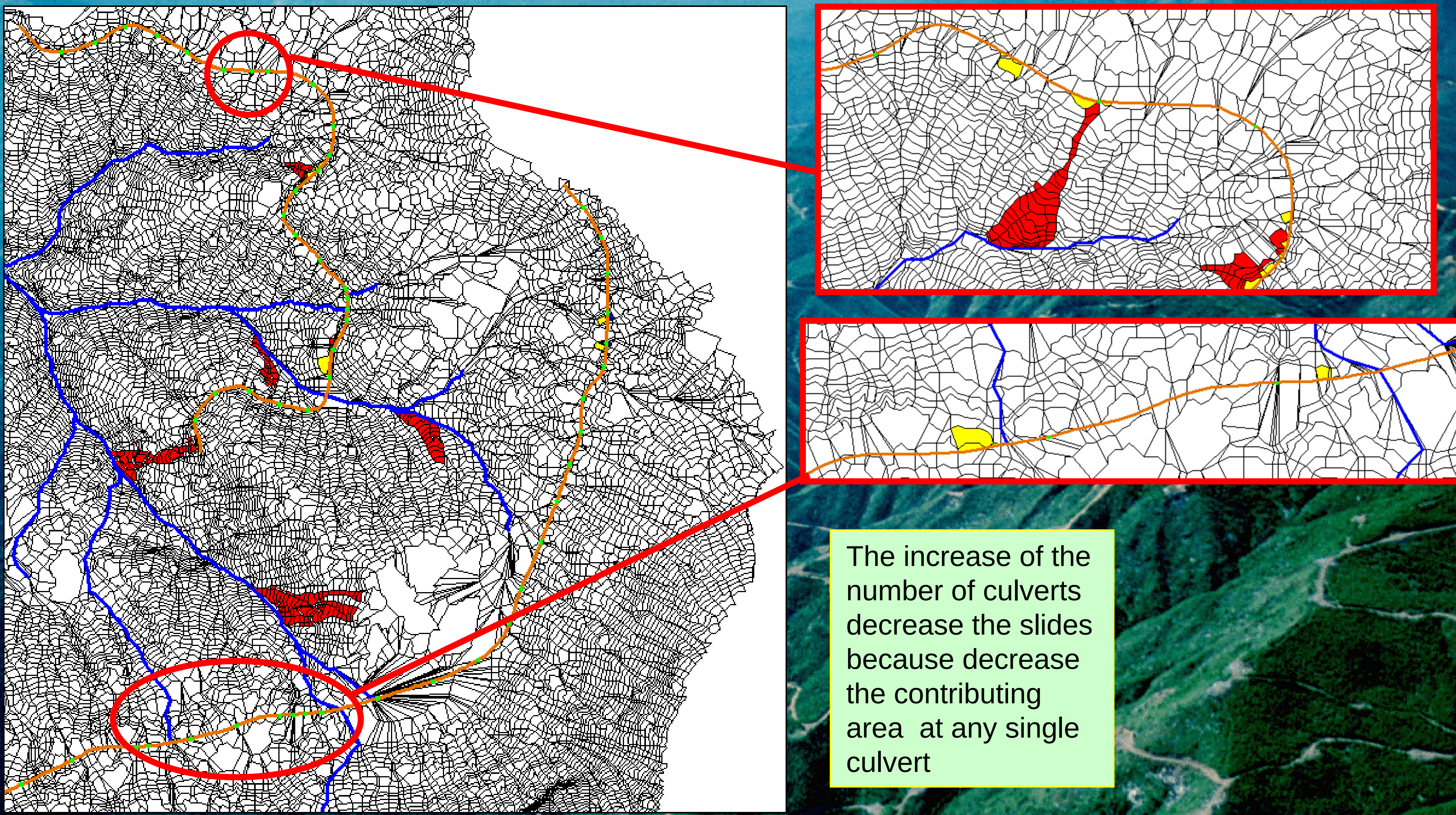


Upslope road: landslides triggering is mainly due to the geometric effect.

Downslope road: landslides triggering is mainly due to the hydrologic effect.

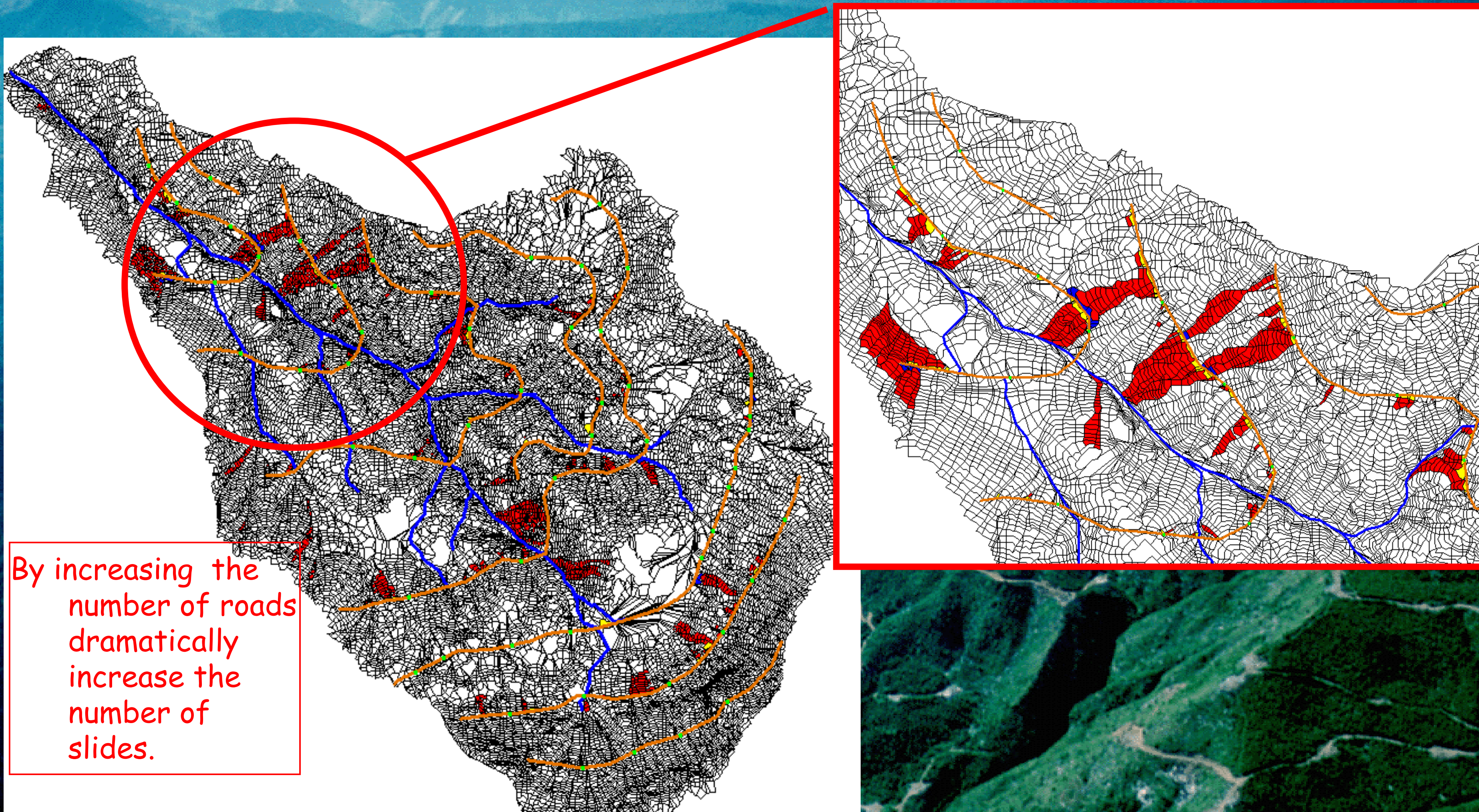
Scenario 1: increase of the number of culverts

Observed slides:



The increase of the number of culverts decrease the slides because decrease the contributing area at any single culvert

Scenario 2: increase of the number of roads



By increasing the number of roads dramatically increase the number of slides.

FIRE INDUCED SHALLOW LANDSLIDES TRIGGERING

Fire Forcing on Hydrological Processes

↓

Increased overland flow, sediment yield and shallow landslides susceptibility

Vegetation cover destruction

- canopy cover
- roots at 10-20 cm of depth

Formation of a water repellent layer

- formation mechanism
- thickness
  - position
    - duration
      - soil type
      - temperature
        - vegetation cover
        - water content

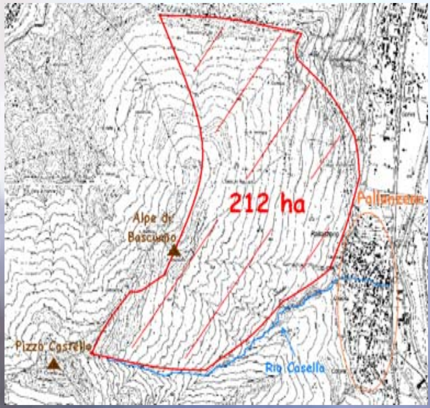
Effects on soil properties

- increase in erodibility
- decrease in infiltration capacity
- decrease of cohesion

Rulli M.C.,Bocchiola D., Rosso R., JoH 2006

THE EVENT OF 18 th OF JULY, 2005

Severe rainfall event. About 40 mm of rainfall dropped in less than 30 minutes (TR= 10 years) on a previously burned soil.



On 16 th March 2005 a severe forest fire occurred in the area of Rio Casella burned more than 70% of the study area.

The Study Area

1.6 km² catchment (Rio Casella) located in the Piedmont, Italy

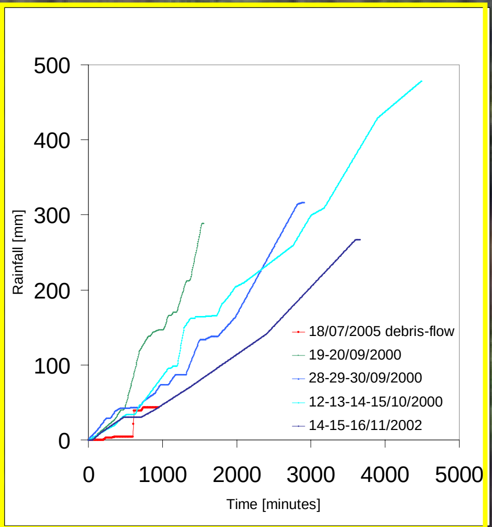
Major Features

Geology: granitic gneiss; in the highest area, large zones with exposed granitic formations
Climate: mediterranean
Rain: mainly in May and October (MAP is 1300 mm)
Vegetation: Chestnut
Hydrography: ephemeral streams
Topografy: steep slopes, elevation range 1600-250 a.s.l.

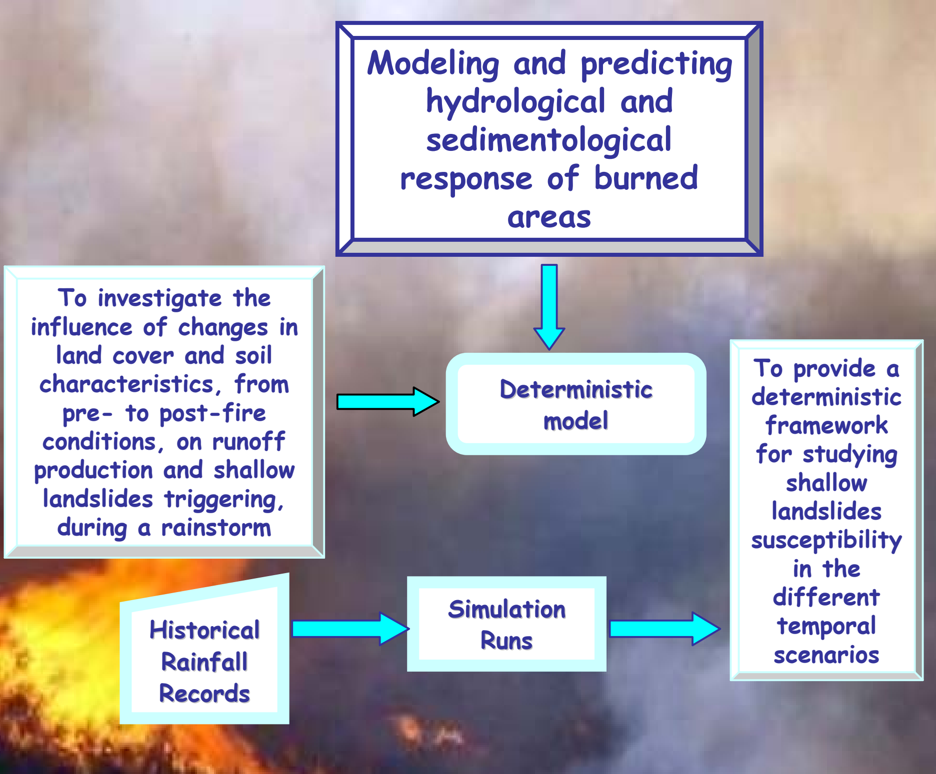
Mass Movement Triggering (30000 m^3)

In the period from the beginning of the year 2000 to the day of the forest fire, 47 rainfall events occurred having or intensity or total greater than the rainfall event triggering the mass movement of July 2005.

It means that the role of forest fire in triggering mass movement should be taken in consideration.



Rulli M.C., Rosso R., GRL 2006



Field Data

Vegetation Survay (Pre; Post and Transient)

Soil depth measuremts

WDPT test

Soil type

Pedology

Geology

Hydraulic conductivity measurements (Pre; Post and Transient)

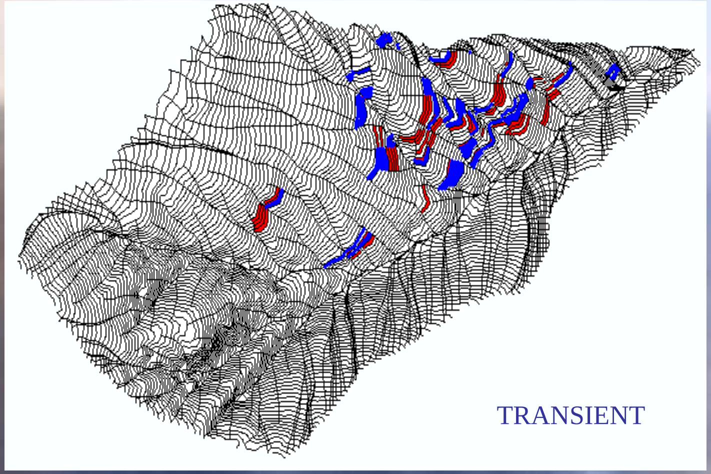
	POST - FIRE	POST-FIRE/ 16 MONTH	PRE-FIRE
Friction Angle [°]	42	42	42
Saturated Soil Spec. Weight [KN/m³]	21.5	21.5	21.5
Cohesion [KPa]	0	4	10
Apparent Cohesion [Kpa]	0	0	0

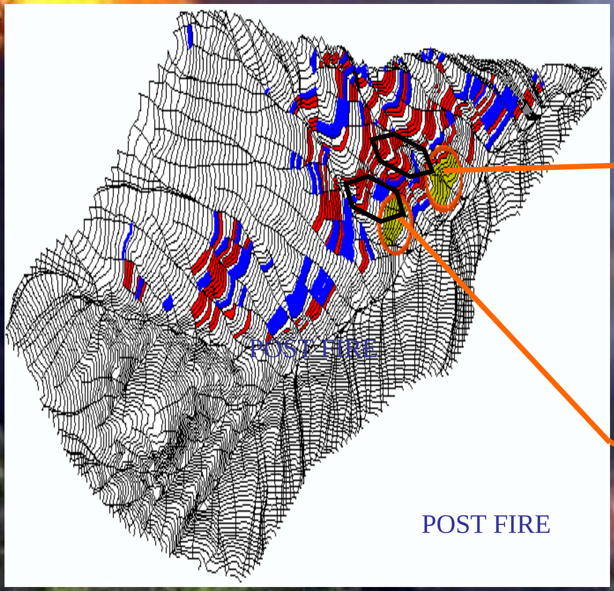
SBM Parameters	POST-FIRE	TRANSIENT/ 16 MONTHS after the forest fire	PRE-FIRE
Soil depth upslope [m]	1	1.5	2.5
Soil depth downslope [m]	1.5	2	3
Ks upslope [m/s]	0.000001 / 0.00005	0.000001 / 0.00007	0.000001 / 0.00015
Ks downslope [m/s]	0.000001 / 0.00005	0.000001 / 0.00007	0.000001 / 0.00015
Multipling factor for horizontal K_s [-]	1	1	1
Rate of decay in K_s with depth [-]	0.3	0.3	0.3
Satured soil water content θ_S [-]	0.4	0.4	0.4
Residual soil water content θ_N [-]	0.1	0.1	0.1
Initial satured store of the bucket [%]	10 - 30	10 - 30	10 - 30
Initial soil water content - upslope [-]	0.1 - 0.2	0.1 - 0.2	0.1 - 0.2
Initial soil water content - downslope [-]	0.1 - 0.2	0.1 - 0.2	0.1 - 0.2

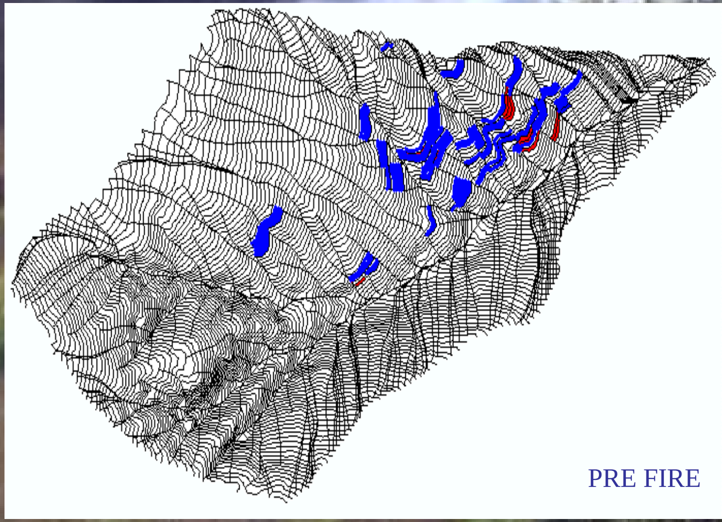
	POST-FIRE	TRANSIENT/ 16 MONTHS	PRE-FIRE
Manning coefficient - Slopes [s $m^{-1/3}$]	0.04/0.015	0.04/0.025	0.04/0.04
Manning coefficient - Channels - upslope [s $m^{-1/3}$]	0.015	0.025	0.04
Manning coefficient - Channel - downslope[s $m^{-1/3}$]	0.015	0.025	0.04
Critical Support Area [-]	50000	50000	50000
Channel Width Scaling Factor [-]	0.26	0.26	0.26
Outlet Flow Width [m]	3.7	3.7	3.7
Time Step for the Kinematic Wave [s]	60	60	60

Temporal Scenarios

- **pre-fire**: the period of time before the forest fire occurred
- **post-fire**: the period from the time when the fire estinguished to the end of the spring in the subsequent year
- **transient**: the period of time required for the restoration of the soil, following fire induced disturbance







Rulli M.C., Rosso R., AWR 2007

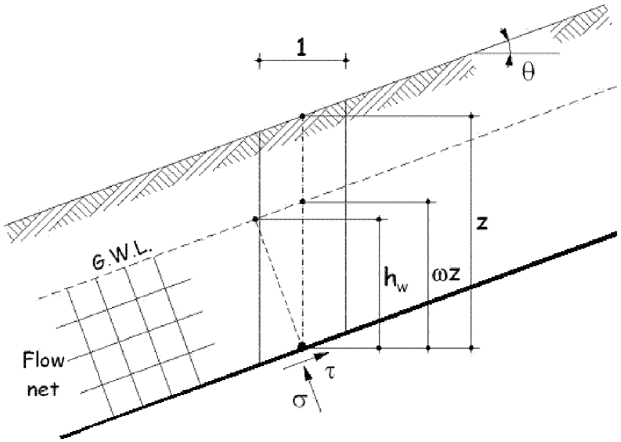
Conclusions:

Anthropogenic and natural activities like roads and forest fires can strongly influence the hydrologic response and shallow landslides susceptibility of upland catchments!

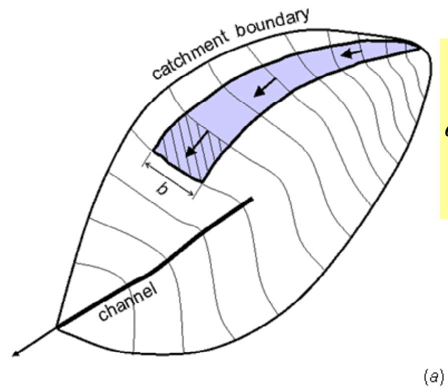
For studying anthropogenic and natural activities influence on shallow landslides triggering it is necessary correctly evaluate the effects of these activities on the hydrological fluxes (generation and direction).

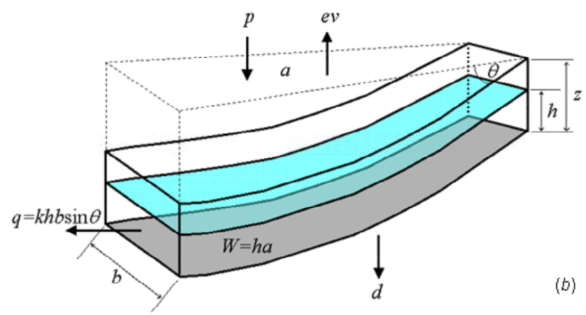
For studying anthropogenic and natural activities influence on shallow landslides triggering it is necessary correctly select the gomechanical model!

THANK YOU!



$$FS = \frac{\left[G_s + e \cdot S_r - \omega \cdot \left(1 + e \cdot S_r\right)\right]}{\left[G_s + e \cdot S_r + \omega \cdot e \cdot \left(1 - S_r\right)\right]} \cdot \frac{\tan \phi'}{\tan \theta}$$





$$\omega = \begin{cases} \frac{p}{p^*}\left[1 - \exp\left(-\frac{1}{A_1}\xi\right)\right] & \text{, if } \xi \le -A_1 \ln\left(1 - \frac{p^*}{p}\right); \\ 1 & \text{, if } \xi > -A_1 \ln\left(1 - \frac{p^*}{p}\right); \end{cases}$$

$$p^* = \frac{Tb \sin\theta}{a}$$

$$A_1 = \frac{e}{1+e} \cdot \left(1 - S_r\right)$$

$$\omega = h/z$$

$$\xi = (p^*/z)t$$

Precipitation threshold for slope instability

Coupling hillslope hydrology with geomechanics yields landslide triggering by precipitation

$$p_{CR}(t)=\frac{T\frac{b}{a}\sin\theta\left[\frac{(G_s+e\cdot S_r)\cdot\left(1-\frac{\tan\theta}{\tan\phi'}\right)}{1+e-e\cdot(1-S_r)\cdot\left(1-\frac{\tan\theta}{\tan\phi'}\right)}-\frac{h_i}{z}\exp\left(-\frac{1+e}{e-eS_r}\frac{Tb\sin\theta}{az}t\right)\right]}{1-\exp\left(-\frac{1+e}{e-eS_r}\frac{Tb\sin\theta}{az}t\right)}$$

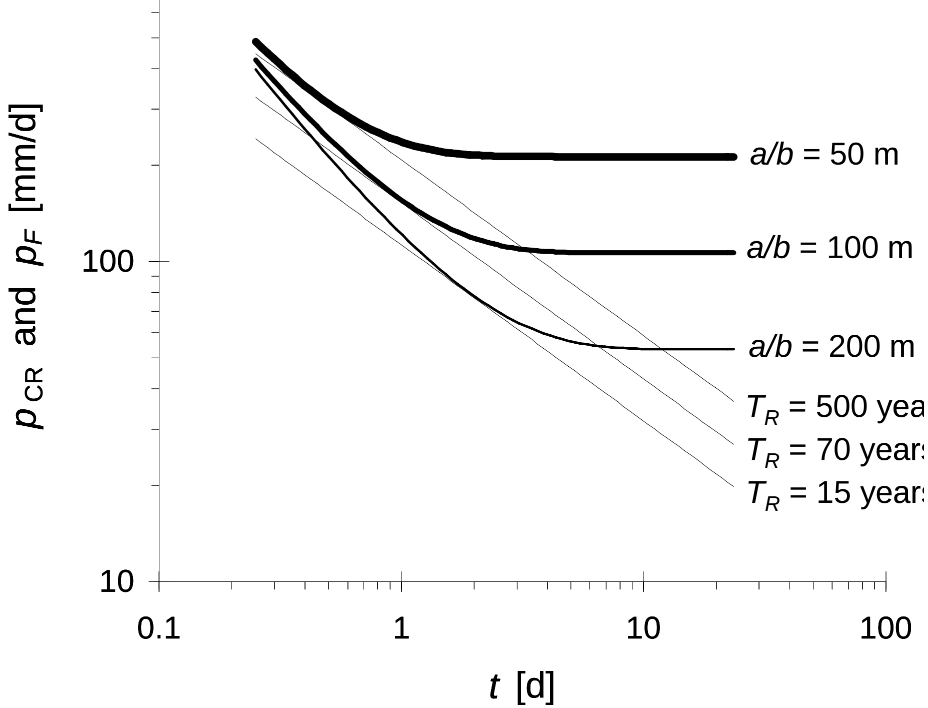
Temporal scale of hillslope evolution

$$p_F(t)=m_1x_Ft^{-(1-n)}$$

The rainfall rate p_F that can be exceeded with a probability of (1 – F) in a year

$$p_{CR}=p_{CR}(t)$$

$$\frac{T\frac{b}{a}\sin\theta\left[\frac{(G_s+e\cdot S_r)\cdot\left(1-\frac{\tan\theta}{\tan\phi'}\right)}{1+e-e\cdot(1-S_r)\cdot\left(1-\frac{\tan\theta}{\tan\phi'}\right)}-\frac{h_i}{z}\exp\left(-\frac{1+e}{e-eS_r}\frac{Tb\sin\theta}{az}t\right)\right]}{1-\exp\left(-\frac{1+e}{e-eS_r}\frac{Tb\sin\theta}{az}t\right)}=m_1x_Ft^{-(1-n)}$$



Maps of Mettman Ridge catchment showing shallow landsliding prone areas in term of return period of potential failure considering initial condition of stable piezometric at the depth of bedrock, $h(0) = 0$ and $h(0) = 0.15$, $\phi' = 45°$, $T = 65$ m^2/d, $\rho_s = 1600$ kg/m^3 and $G_s = 2.60$.