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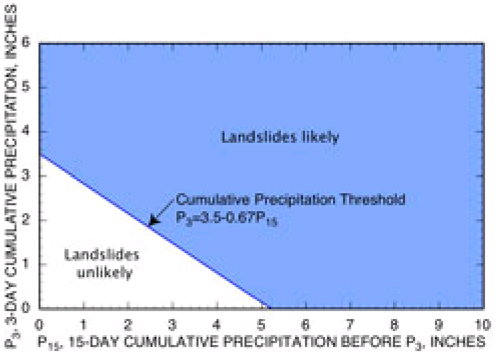
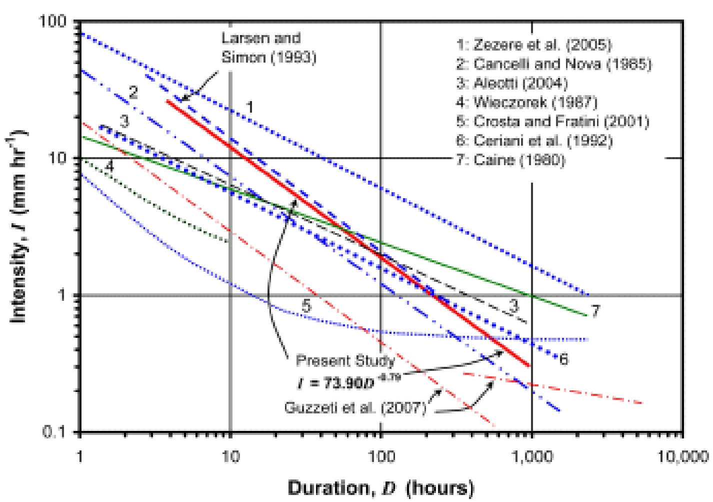
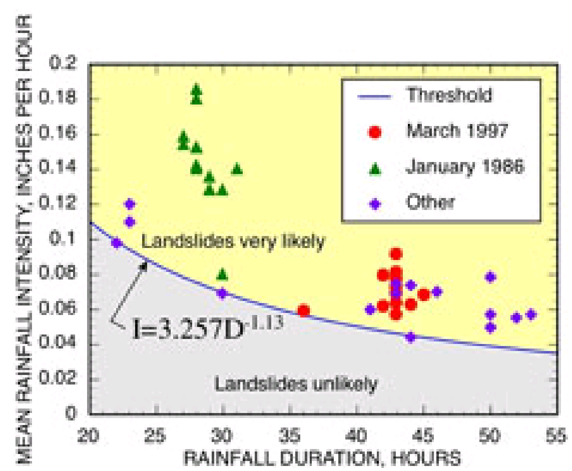


ASSESSMENT OF LANDSLIDE TEMPORAL FREQUENCY

Malet Jean-Philippe, Remaître Alexandre

CNRS, University of Strasbourg, France





Content

- Single landslide vs. landsliding events

- Approaches for the assessment of probability of occurrences
  - *#1 Heuristic approach*
  - *#2 Correlation with triggers*
  - *#3 Magnitude – Frequency relationships*
  - *#4 Probabilistic modelling*

- Data for frequency assessment

What is a landslide event?

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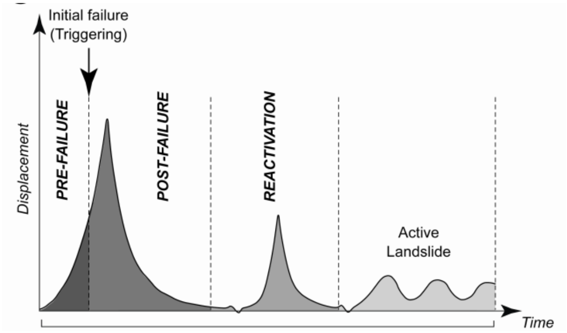
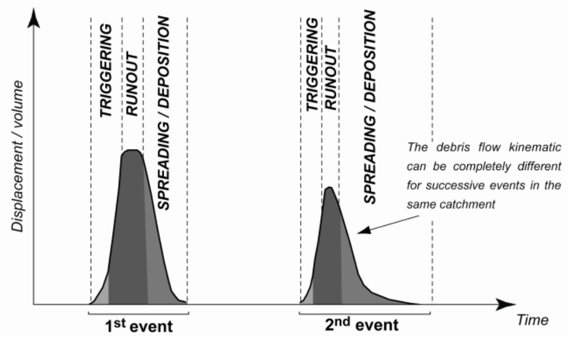
Single landslides

+ Shallow slide: nearly instantaneous and unique
+ Active large landslide: acceleration phases
+ Debris flow, rockfall: possible unique or multiple successive events





Landsliding event

Multiple occurrence of landslides in a region caused by a trigger (i.e. intense rainfall, earthquake)

Approaches for the assessment of probability of occurrence of landslides

+ Heuristic approach (expert judgement). Use of geomorphological evidence

+ Correlation with triggers. Frequency of the critical thresholds

+ Historic data. Magnitude – frequency relations (m-F)

+ Probability analysis taking into account the uncertainty in slope parameters (geometry, shear strength, etc) and the modelling of slope hydrology/slope stability

Picarelli et al. 2005. Hazard characterization and quantification.
In O. Hungr, R. Fell, R. Couture and E. Eberthardt (editors)
Landslide Risk Management. Taylor and Francis, London. pp. 27-61

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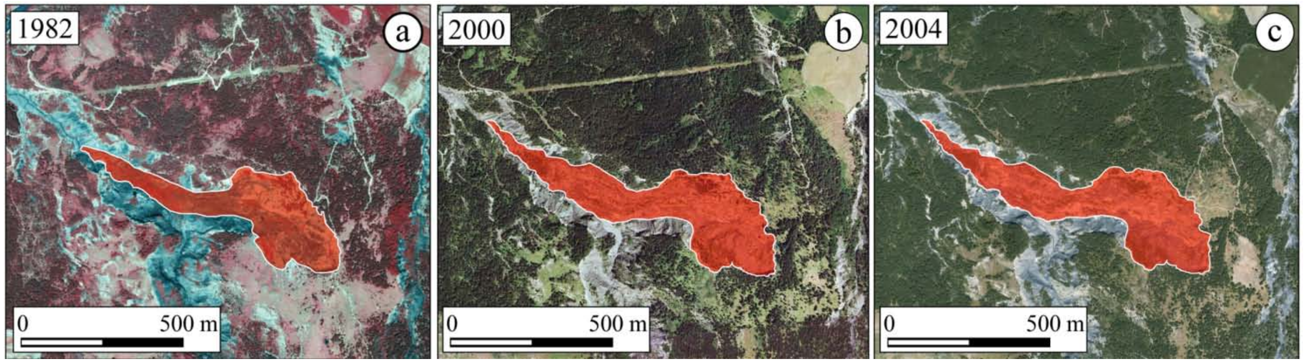
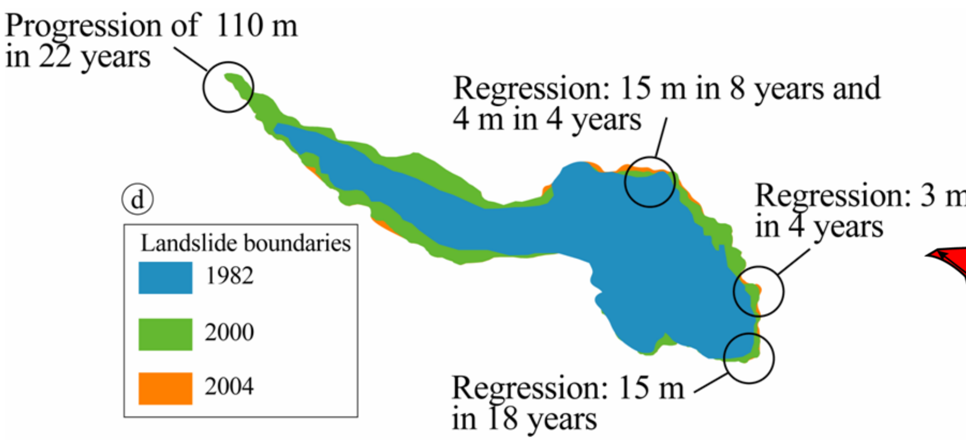
Approach #1: Heuristic model / mapping

+ Early attempts of landslide hazard mapping (Plan ZERMOS, PPR)



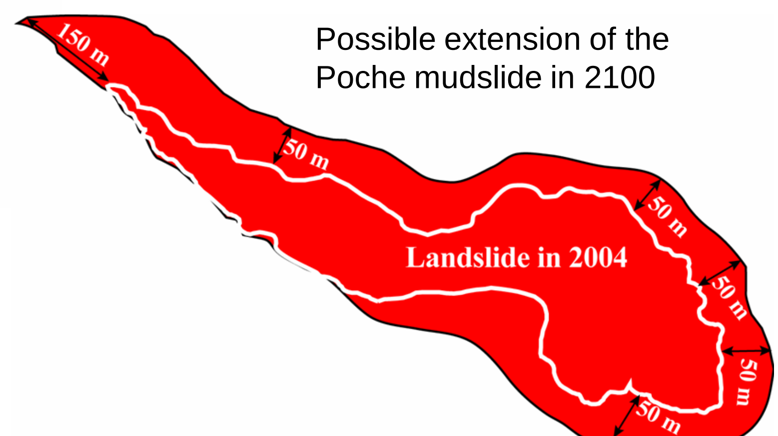
Aerial photographs interpretation



Changes in landslide contours

Hazard zoning
(possible extension for the next 100 yrs, 4 age generations)

Possible extension of the Poche mudslide in 2100



Approach #2: Correlation with triggers (rain)

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+ Assumption:

Frequency of the landslides is that of the triggering event

+ Restrictions/drawbacks:

Different triggers may cause landslides in a region (rainfall, snow melt, earthquakes, flooding-slope undermining, etc)

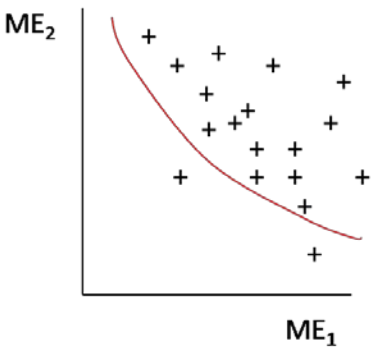
Triggering events of similar intensity may have different consequences on the slopes

Approach #2: Correlation with triggers (rain)

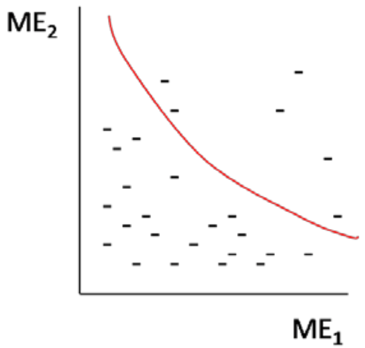
Type of thresholds

Cepeda & Devoli (2008)

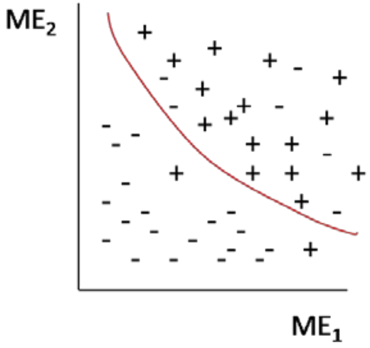
(A): Threshold defined as a lower bound to landslide-triggering conditions (”+” symbols)



(B):Threshold defined as an upper bound to conditions that did not trigger any landslides (”-” symbols). Very useful for an initial calibration of thresholds in newly instrumented regions.



(C): Threshold defined as a boundary between <u>triggering and non-triggering conditions</u>.
This is the preferred approach for calibrating thresholds for use in EWS.
The challenge in optimising the threshold model is to minimize the number of false alarms (”-” symbols above the threshold) and missed events (”+” symbols below the threshold).



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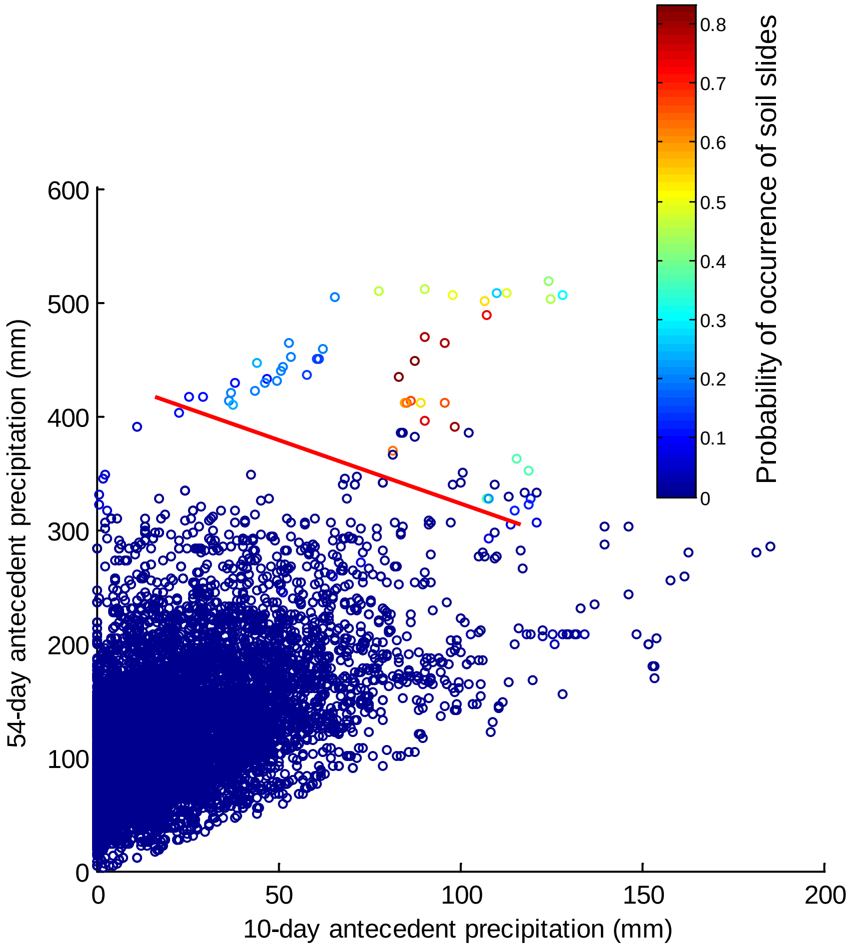
Approach #2: Correlation with triggers (rain)

Three type-C threshold models based on antecedent rain

$A_n = \alpha_n$ *: single value of antecedent rain (calibration of n parameter and* α *threshold value)*

$A_n = \alpha_n$ and $A_p = \alpha_p$ *: two values for two different periods (use of classification tree)*

$1 + \alpha_1 A_n + \alpha_2 A_p = 0$ *: linear combination of 2 antecedent rain conditions*



A_n and A_p:

antecedent *n*-day and *p*-day precipitation

$\alpha_n, \alpha_p, \alpha_1, \alpha_2$:

constants of the model

Approach #2: Correlation with triggers (rain)

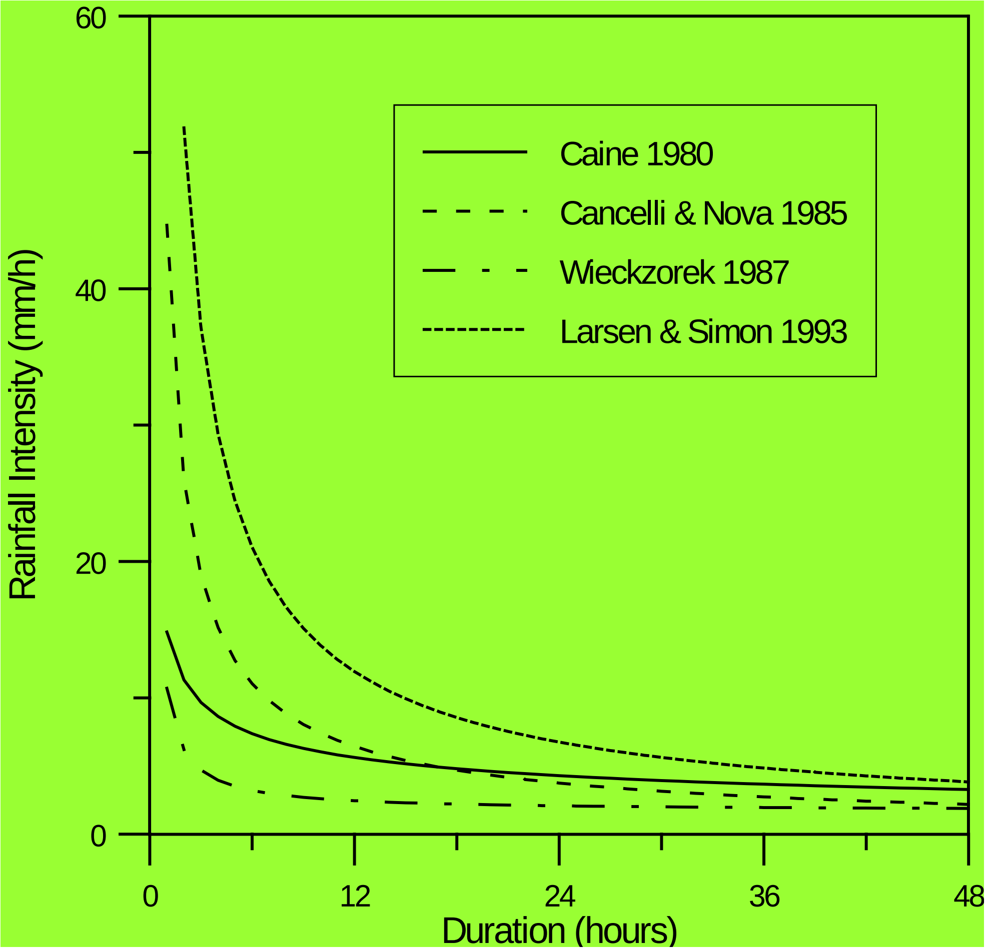
Most commonly used type-C threshold model (I-D model, power law)

$$I = \alpha D$$

Caine (1980):

$$I = 14.82\ D^{-0.39}$$

where I, in mm/h
D, in hr



Approach #2: Correlation with triggers (rain)

Several I-D relationships available ….

Equazione	Autori	Tipo di dati Ambito territoriale
$I = 14.82\ D^{-039}$	Caine (1980)	Dati mondiali, soglia per tutto il mondo
$\text{Log}\ I = 1.65\text{-}0.78\ \log D$	Cancelli e Nova (1985)	Dati evento, Alpi Centrali (Valtellina)
$D = 46.1\ \text{-}3.6 \cdot 10^3 I + 7.4 \cdot 104 I^2$	Cannon e Ellen (1985)	Dati evento, California
$D = 0.90/(I\text{-}0.17)$	Wieczorek (1987)	Dati evento, California
$I = 20\ D^{-0.55}$	Ceriani *et al.*, (1994)	Dati eventi storici, Alpi Centrali (Valtellina)
$I = 19\ D^{-0.50}$	Aleotti (2004)	Eventi storici, Piemonte
$I = 12.7\ D^{-0.53}$	Bolley e Oliaro (1999)	Dati evento, Alpi piemontesi
Non specificata	Crosta e Frattini (2001)	Dati mondiali, tutto il mondo

Approach #2: Correlation with triggers (rain)

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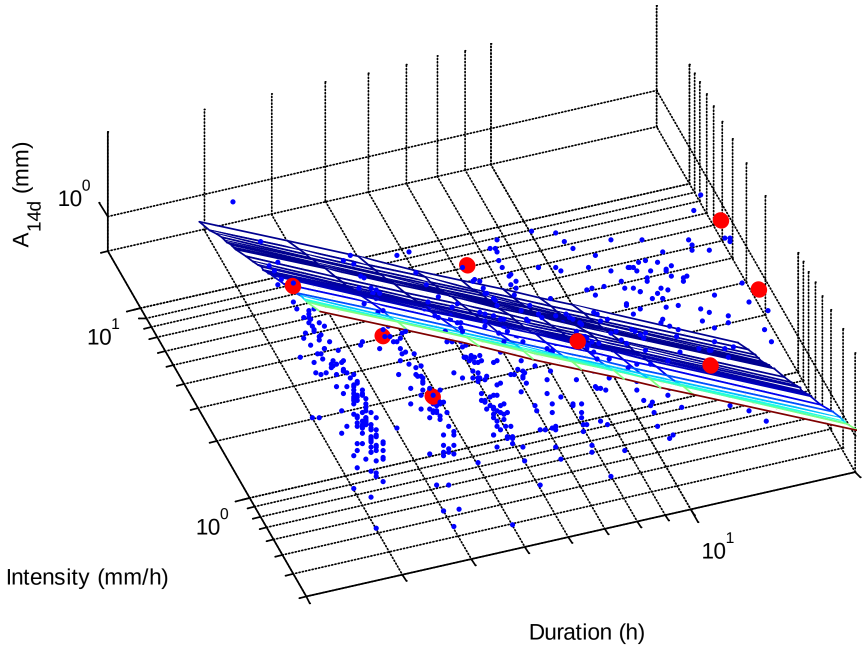
Generalization of I-D model

$$I = [\underbrace{\alpha_1 A_n^{\ \alpha_2}}_{\alpha \text{ in I-D model}}] D^{\beta}$$



where:

I, *D* and β as in *ID* model
A_n: antecedent *n*-day precipitation (mm)
α_1 and α_2: constants of the model

➔ the term in brackets account for the effects of antecedent precipitation
➔ the model requires a calibration of the value of "n", and the constants $\alpha 1$, $\alpha 2$ and β

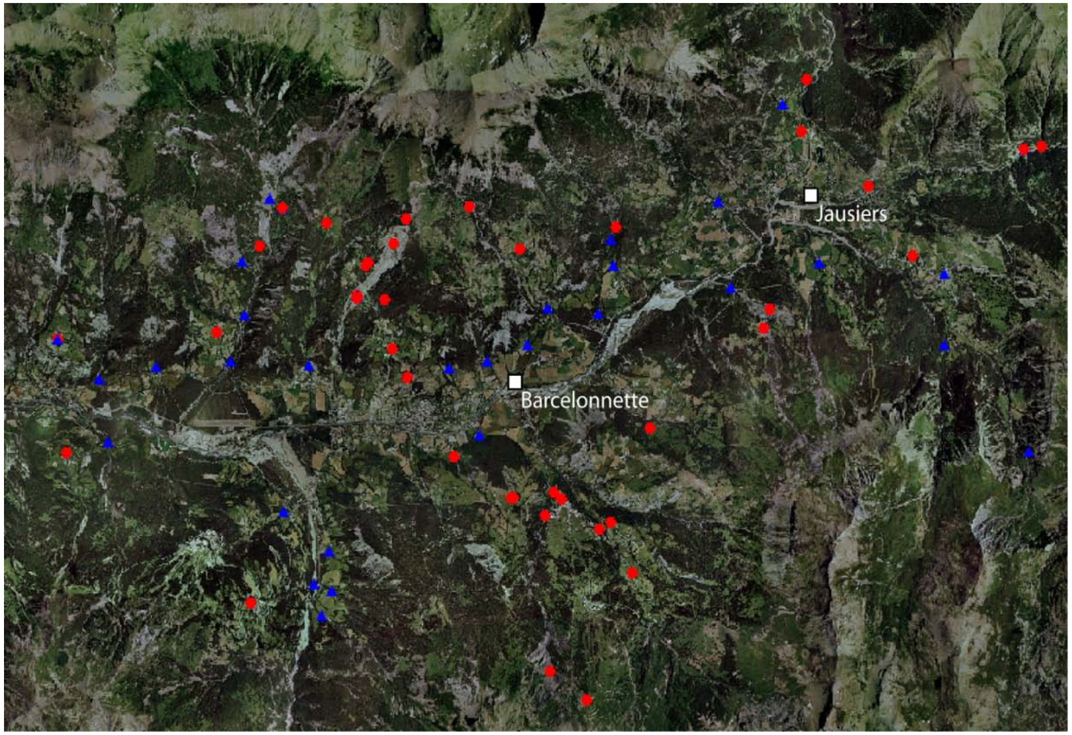
Cepeda, Nadim, Høeg & Elverhøi (2009)

Approach #2: Correlation with triggers (rain)

Example of application: Barcelonnette, France

+ Type of events:
  - Slides
  - Debris flows

+ Precipitation data:
  - Hourly



Blue: debris flows
Red: soil slides

Cepeda, Malet & Remaître (2011)

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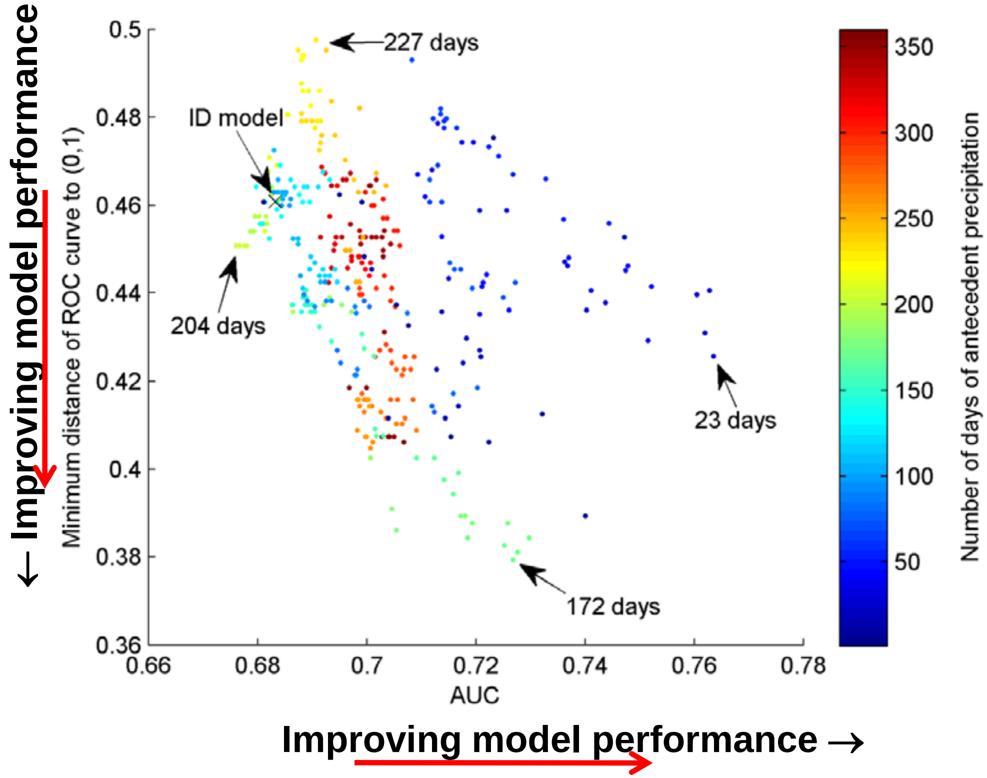
Approach #2: Correlation with triggers (rain)

Comparisons of ID & IAD models

Cepeda, Malet & Remaître (2011)

Test of 360 different IAD models (varying n = 1,2,3, ..., 360 days) and ID model (Caine).



The performance of the model improves as we move to the right and to the bottom. The colours of the dot markers indicate the value of ”n”.

The best performance in terms of AUC is for n = 23 days, and the worst for n = 204 days.
The ”x” marker shows the performance of the ID threshold (Caine)

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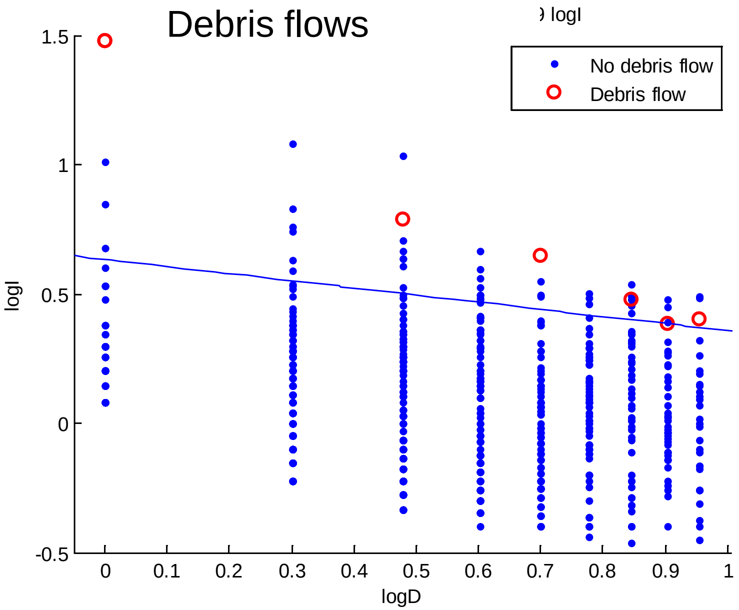
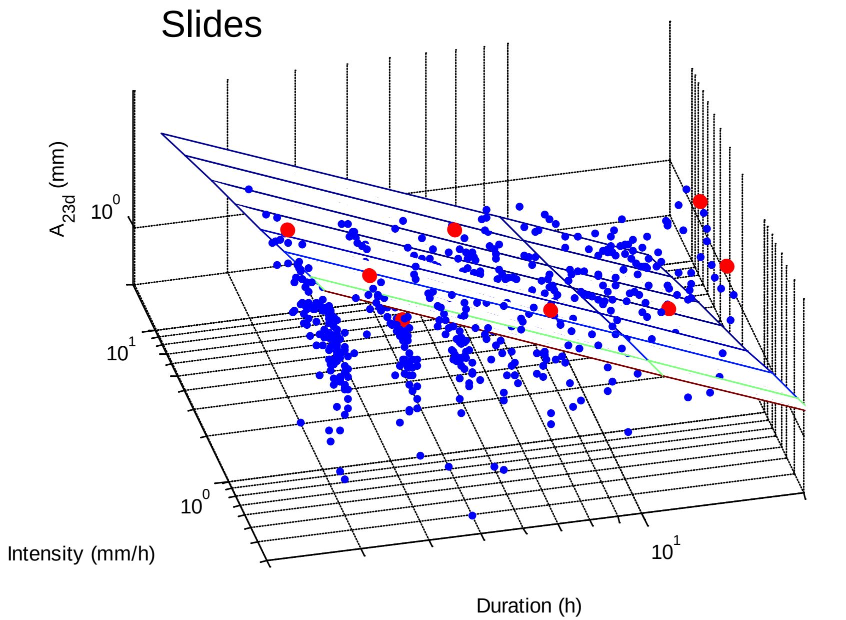
Approach #2: Correlation with triggers (rain)

Results: Barcelonnette

Cepeda, Malet & Remaître (2011)





***D*: 1 to 9 hours** $I = 4.297 D^{-0.275}$

***D*: 3 to 17 hours** $I = 181.2 A_{23d}^{-0.6788} D^{-1.5163}$

➔for debris flows, a traditional ID threshold is sufficient
+ triggering rainfall 1 to 9 hrs
+ no need of antecedent rain

➔for slides, an improved performance is achieved with the IAD model
+ triggering rainfall 3 to 17 hrs
+ need of antecedent rain of 50 days

Approach #3: Magnitude-frequency relationships

Approach taken from seismology

Gutenberg- Richter power law: $$\log N\left(m\right) = a - bM$$

N number of events equal of greater than M

M magnitude

a and b , constants

Need of accurate landslide catalogues

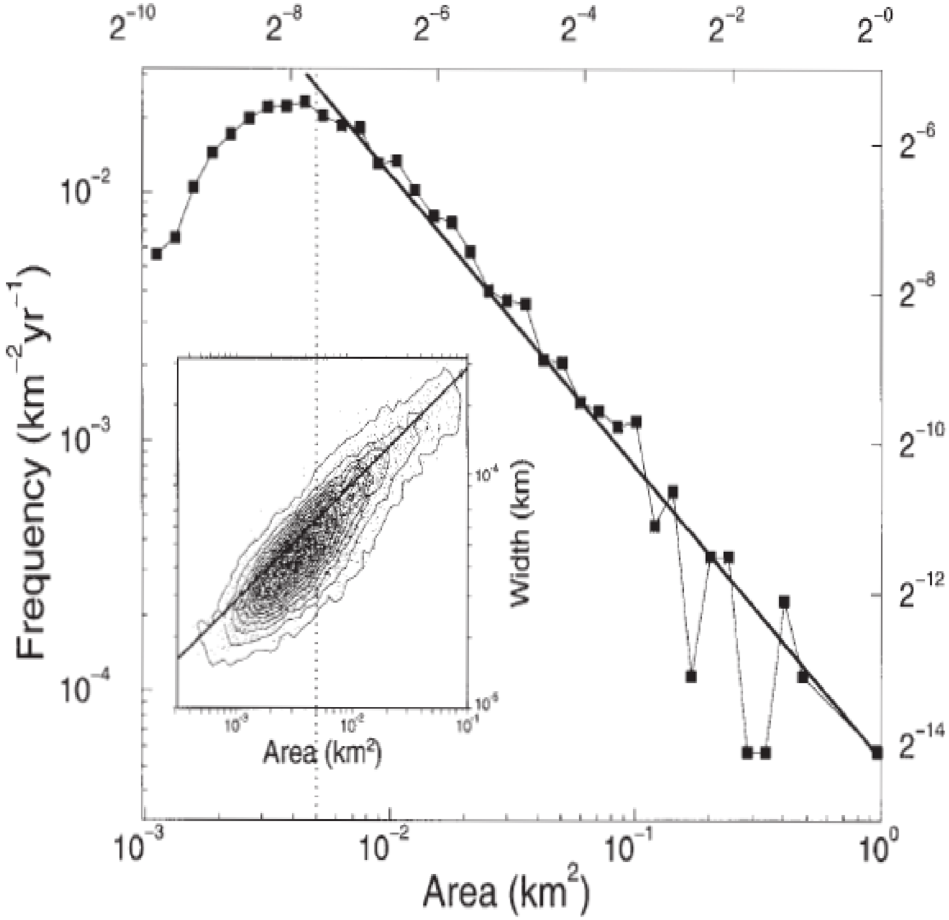
Approach valid for landsliding events (several events initiated by 1 trigger)

Approach #3: Magnitude-frequency relationships

For landslides, several authors (Hovius et al. 1997; Pelletier et al. 1997) found a typical relationship:

$$N_E = C A_L^{-\beta}$$

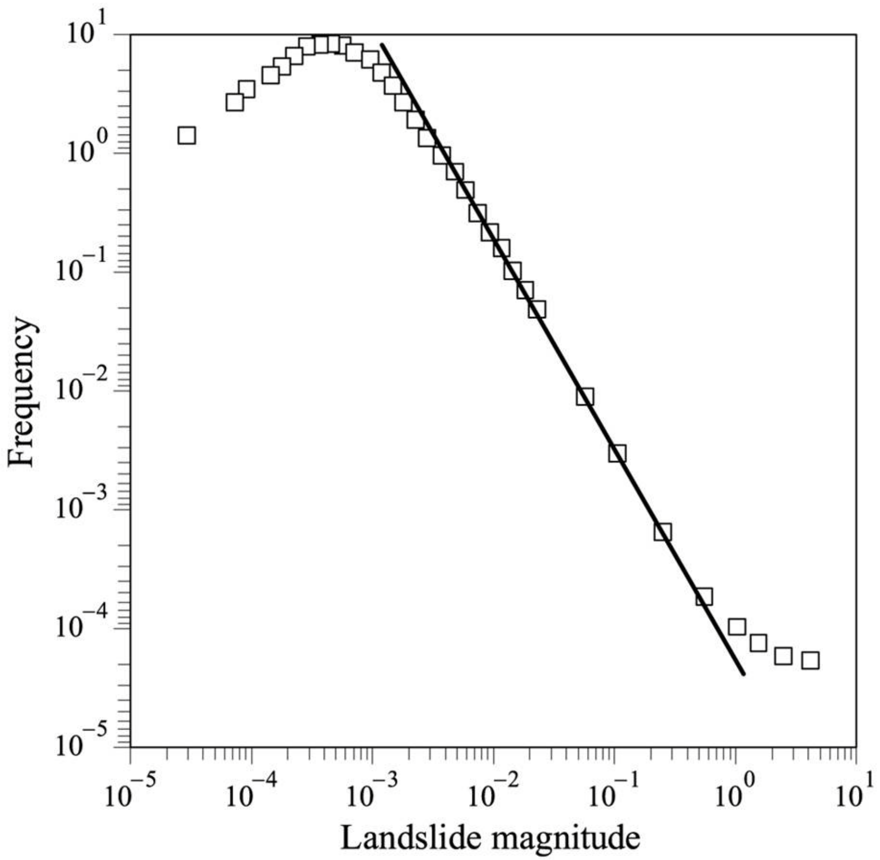
N_E number of events equal or greater than A
A magnitude (area)
C and β , constants



Pelletier et al. (1997)

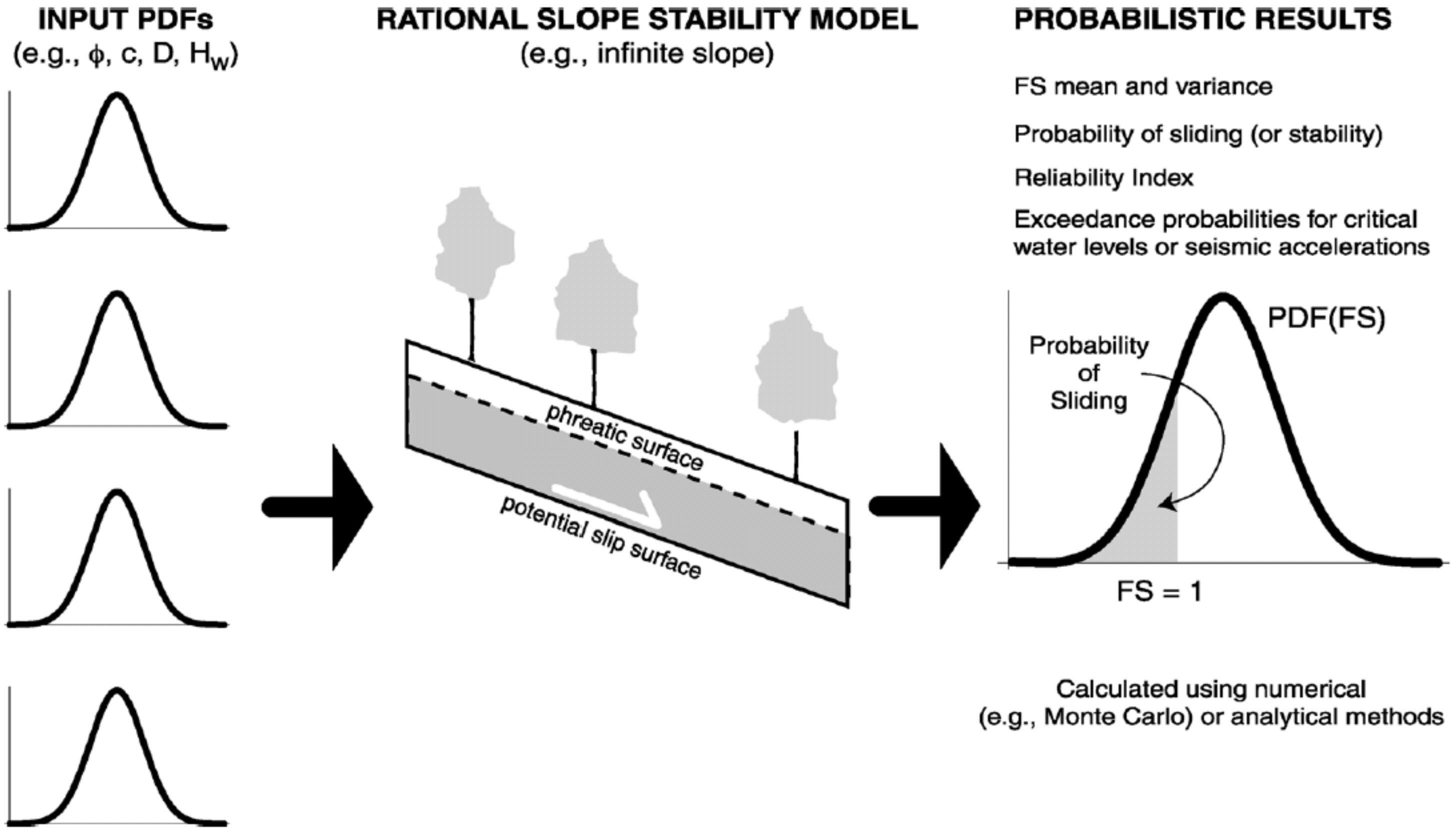
Approach #3: Magnitude-frequency relationships

The linear segment of these log-log relationships have been suggested for assessing (extrapolating) frequency of both mid-size and large landslides (Malamud et al., 2004; Picarelli et al., 2005)



Malamud, Turcotte, Guzzetti, & Reichenbach (2004)

Approach #4: Probabilistic modelling



Safety factor (engineering) approach ➔ probability of unstable slope segments (e.g. pixels)

$$FS = \frac{c_r + c_s + [q_t + \gamma_m D + (\gamma_{sat} - \gamma_w - \gamma_m) H_w D] \cos^2 \beta \tan \phi}{[q_t + \gamma_m D + (\gamma_{sat} - \gamma_m) H_w D] \sin \beta \cos \beta}$$

Haneberg (2004)

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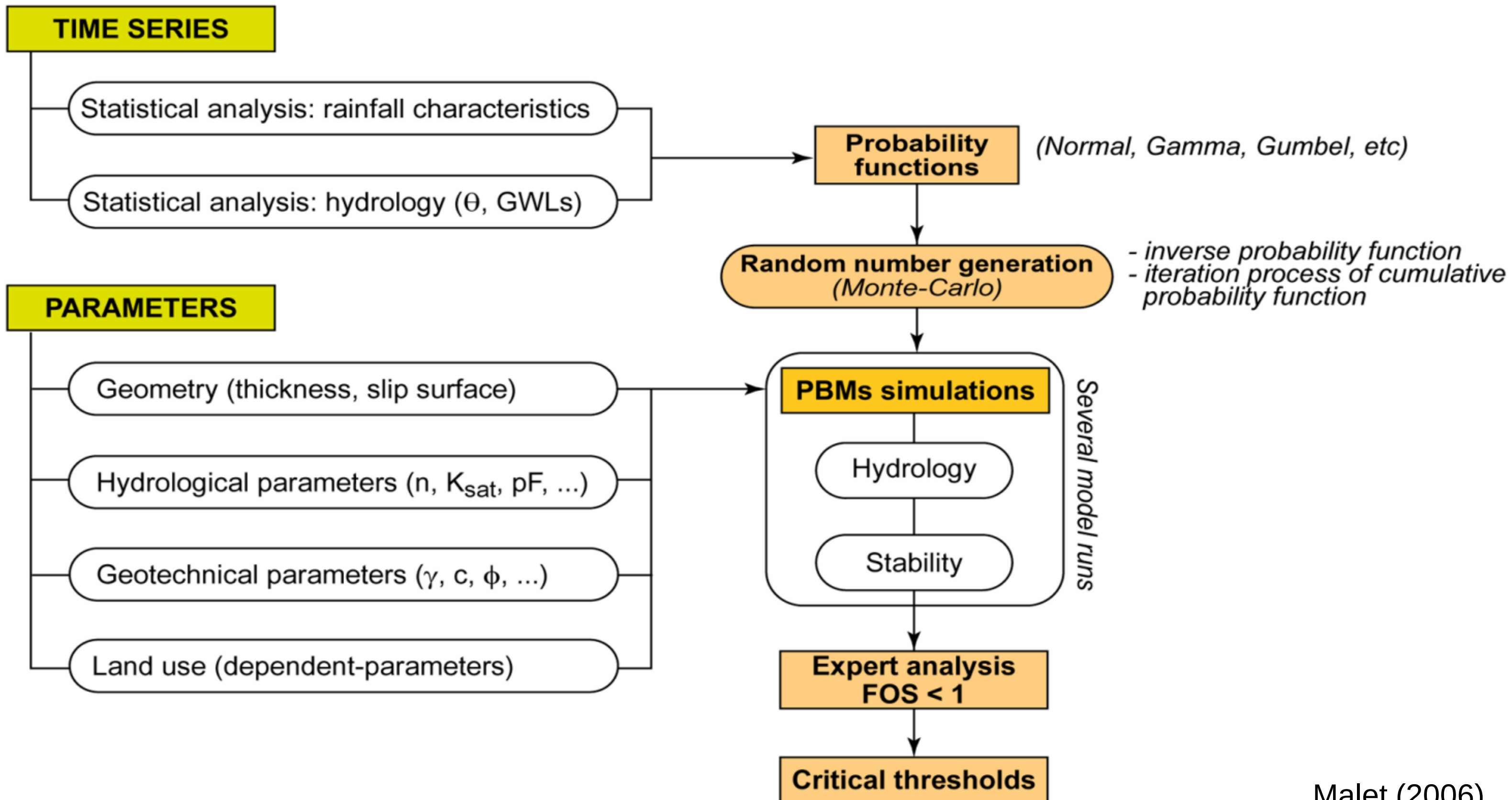
Approach #4: Probabilistic modelling

Estimation of thresholds and probabilities of failure through PBMs and Monte-Carlo simulations (scarcity of data relating landslide movement & hydrological triggers)



Malet (2006)

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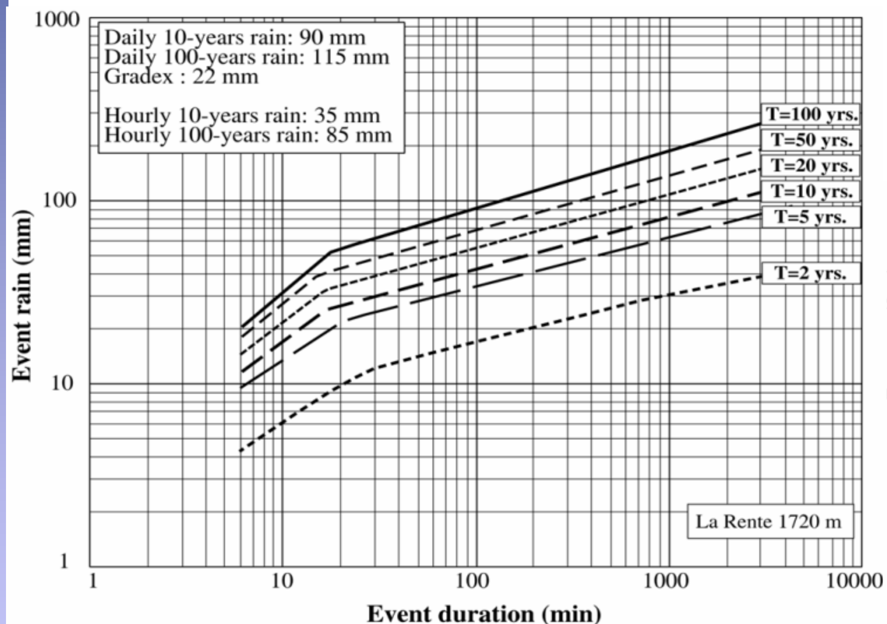
Approach #4: Probabilistic modelling

Probability Density Functions for rainfall time series

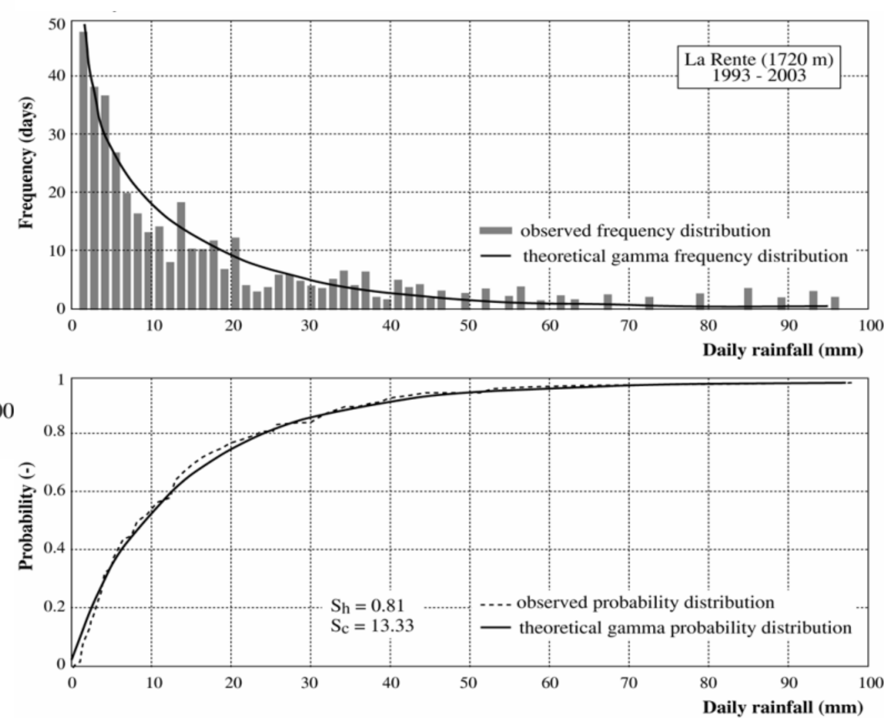
• La Rente dataset
Depth-Duration analysis



• Gamma-type rainfall distribution

$$P(x) \quad \frac{1}{S_c \times \Gamma(S_h)} \times \left(\left(\frac{x}{S_c}\right)^{S_h-1} \times \exp\left(\frac{-x}{S_c}\right)\right)$$

$$F(x) \quad \Gamma_i\left(S_h, \frac{x}{S_c}\right)$$



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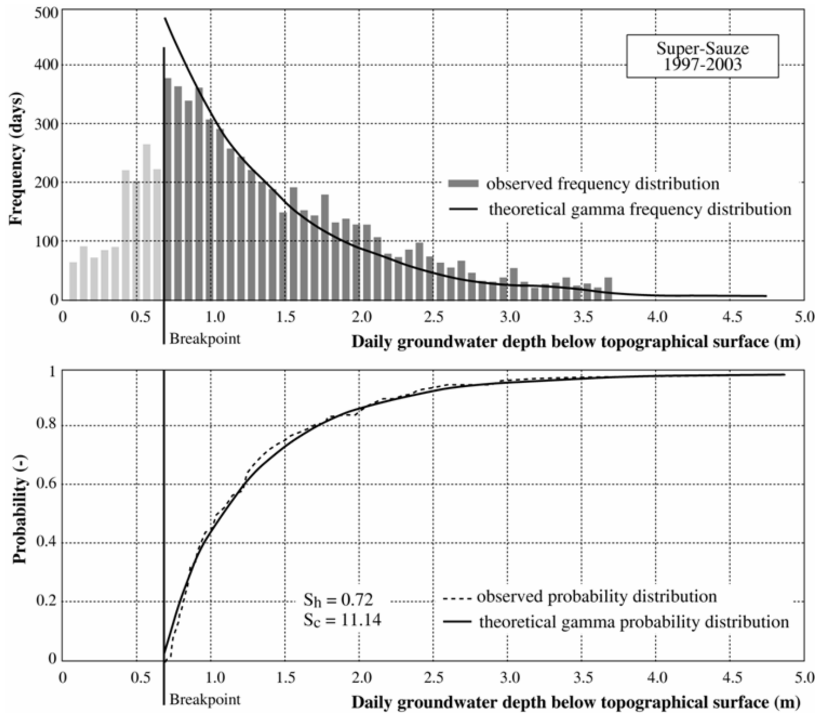
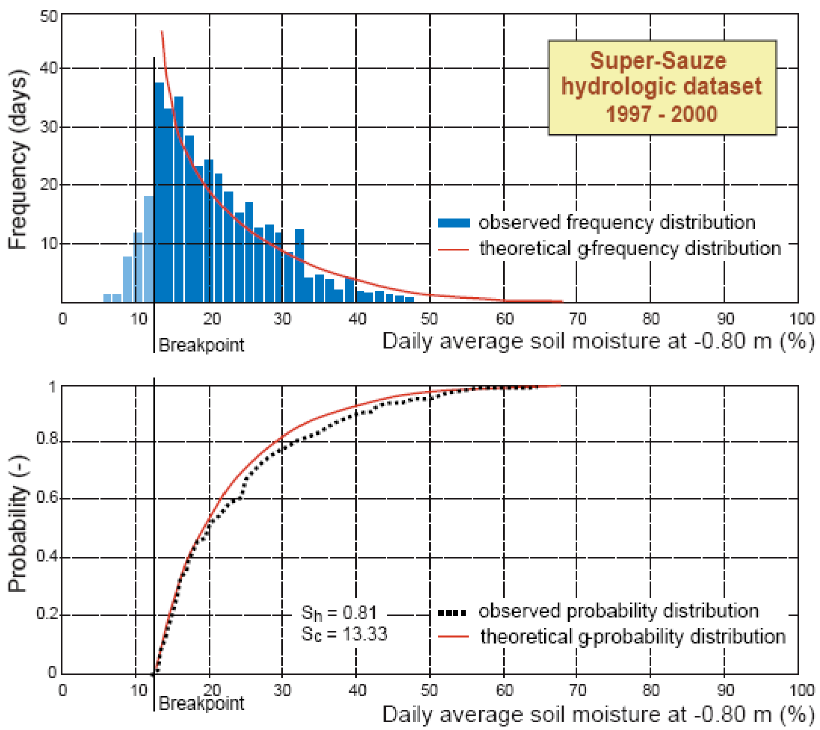
Approach #4: Probabilistic modelling

Probability Density Functions for initial slope conditions

Daily groundwater level distribution functions



Daily soil moisture distribution functions



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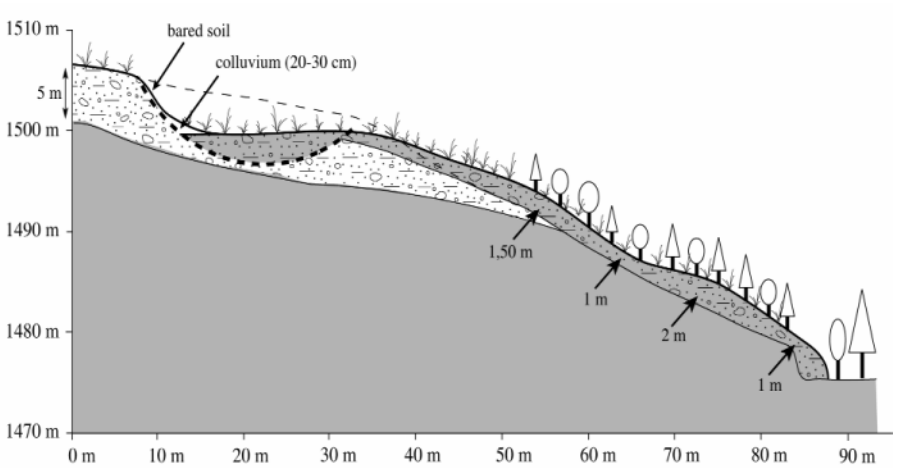
Approach #4: Probabilistic modelling

Slope parameters



Example:
Shallow rotational slides

+ Input parameters

Constant parameters

Hydrology:
- n: 0.50
- K_{sat}: 10 mm.day^{-1}
- pF: h_a = 0.04 ; α = 14.0

Geotechnics:
- γ: 17 kN.m^{-3}
- c': 5 kPa
- ϕ': 27°

Variable parameters (*Monte-Carlo simulations*)

Rainfall:
- duration
- intensity

Hydrology:
- initial GWL
- initial θ

➔ **> 200 model runs**
➔ **timestep: 1 hour**

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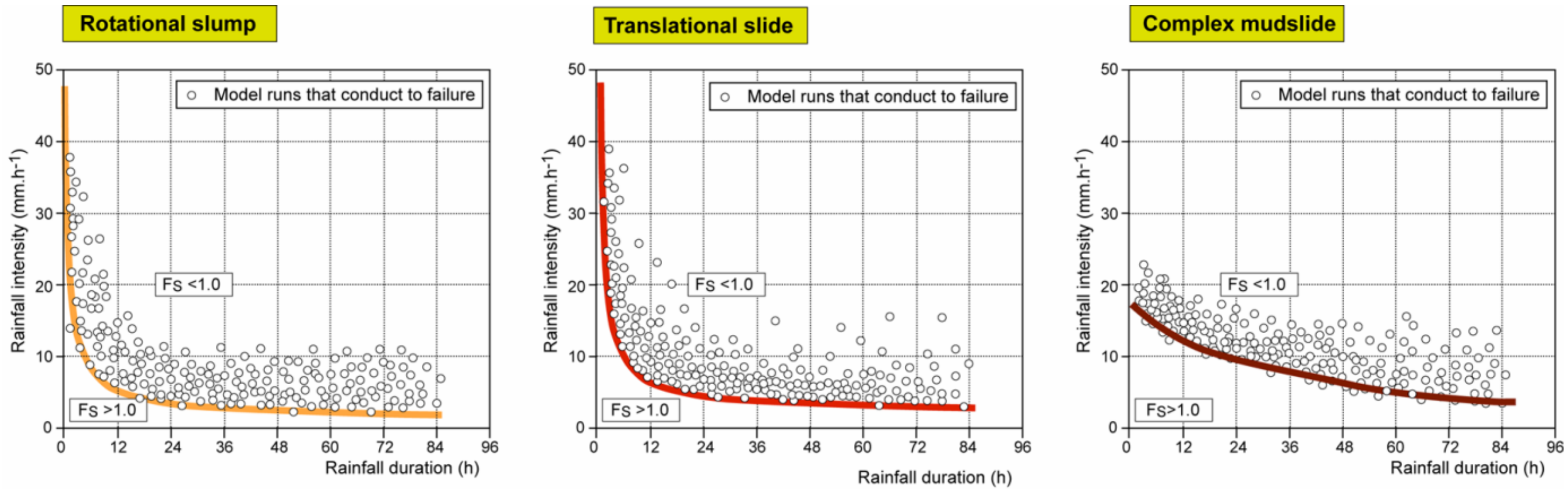
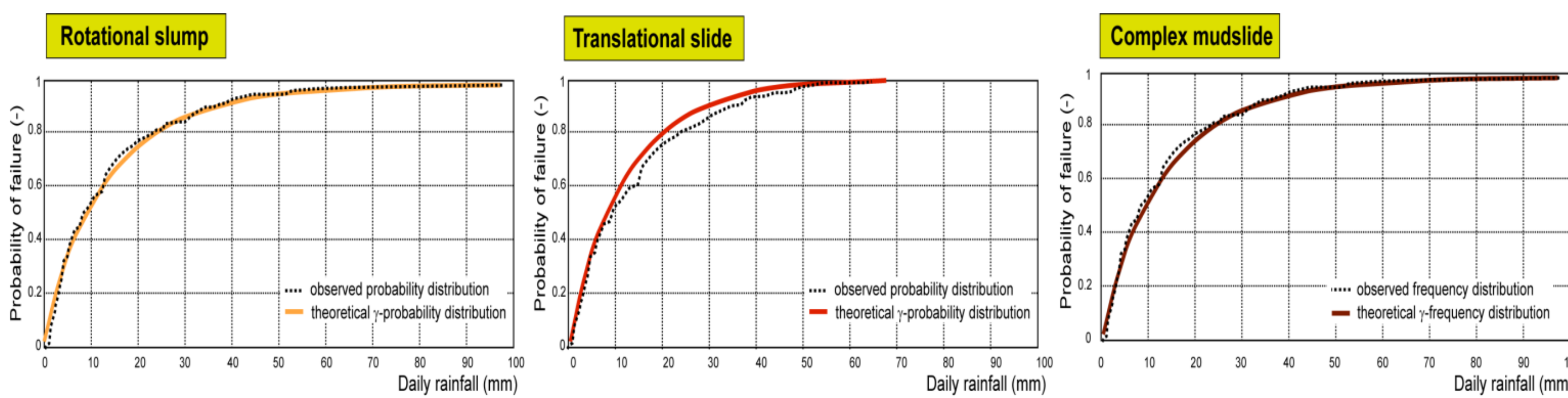
Approach #4: Probabilistic modelling

‘Simulated’ rainfall thresholds for the landslide types in Barcelonnette



Associated probabilities of failure (spatial & temporal)



Conclusions

+ Magnitude-frequency (m-F) relations are difficult to obtain in a single site (except for debris flows and rockfalls). It is often possible for a region.

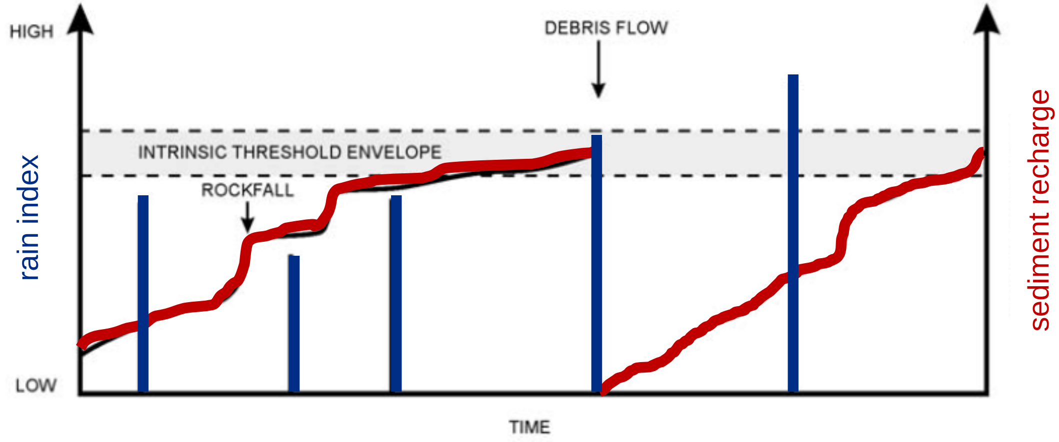
+ Determining landslide frequency requires accurate and detailed landslide catalogues

Accordingly, the term 'event' has to be clearly defined:

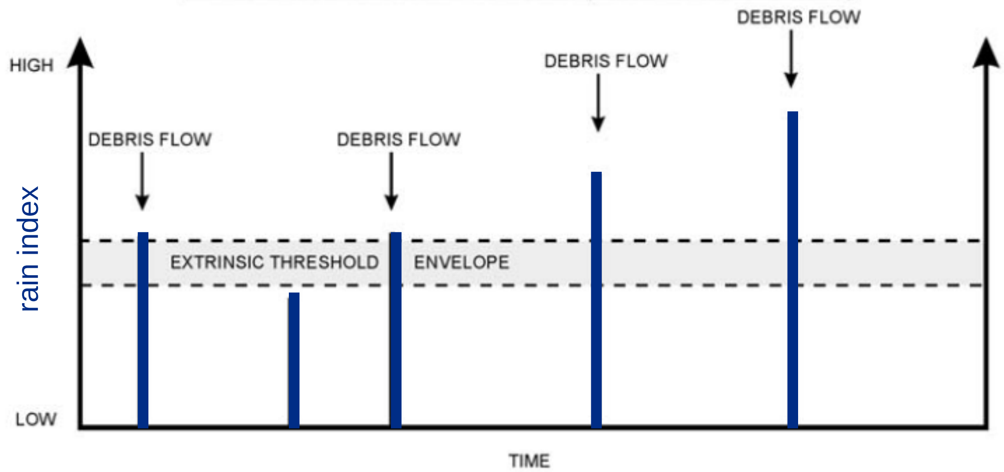
- event of acceleration phases for large landslides
- event of 'unique' slope failure
- ....

Conclusions

+ Frequency of the triggers does not directly provides the frequency of the landslides



sediment supply-limited catchment



sediment supply-unlimited catchment

Conclusions

+ Reconstructing landslide series is a pre-requisite

- Some historical records are not complete or they are too short
- Validity of the extrapolation of m-F relations for large landslides has not been checked yet
- m-F relationships are not conceived for assessing landslide reactivation events !

+ Methods to define landslide catalogues

- Landslide incident records
- Historical archives
- Reconstruction of event time series (dating, etc)
- Monitoring networks
- Remote-sensing techniques

Conclusions

Source	Type of document	Age Output	Time range (yr)
Technical reports	Landslide incident records (continuous inventories)	Either exact or bracketed date of the event occurrence	$0\text{-}10^2$
	Documented disaster events	Exact date of the event occurrence	$0\text{-}10^2$
Instrumental	Continuous monitoring systems	Exact date of the event	0-30
	Episodic monitoring systems	Either exact or bracketed date of the event occurrence	0-60
Historical Archives	Historical archives	Either exact or approximate date of the event	$0\text{-}5\text{x}10^2$
	Maps	Minimum age	$0\text{-}5\text{x}10^2$
Remote sensing	Aerial photographs	Exact date of the event occurrence, bracketed age, minimum age	0- 70
	Satellite images	Exact date of the event occurrence, bracketed age, minimum age	0-35

Corominas & Moya (2008)

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