Applying a change-point detection method on landslide time series: the case of the Torgiovannetto quarry rockslide (Central Apennines, Italy)

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Mitigation of the landslide hazard

- Static approach (prevention): mapping of the landslide susceptibility (geology, geomorphology, land use)

- Dynamic approach: predict the spatial-temporal occurrence of landslides
  → Investigation of the temporal initiation of landslide
  → For rainfall triggered landslides: rainfall intensity-duration curves, physically-based models of the soil wetting
Dynamic approach

Dynamic approach → May be difficult to implement → Especially when the triggering is multiparametric

Rainfall + soil moisture, anteceding rainfalls (Godt et al., 2006; Ray & Jacobs, 2007; Ponziani et al., 2012; Brocca et al., 2012)

Rainfall & soil moisture thresholds → early warning system (www.cfumbria.it) for the Torgiovannetto rockslide

LANDWARN
Object under investigation

Torgiovannetto rockslide
Abandoned stone quarry
Motion of an unstable corner (182,000 m$^3$), detected since 2003 (Intrieri et al., 2012)
Extensometer (13) network since 2005 and 1 weather station

Quiescence and active periods dependent on the rainfall pattern
Decrease of the shear stress along the bedding planes due to the increase of the pore pressure?
The data

Ext11: one of the most reliable sensors (Brocca et al., 2012)

At the top of the slope, on the main fracture of the quarry area

Intieri et al., 2012
Multiple change-point detection

Change-point detection: important issue in geophysics

"One slope or two? Detecting statistically significant breaks of slope in geophysical data, with application to fracture scaling"
Main et al., 1999, GRL

We adopt a more general approach than Main et al's → Non-parametric technique introduced by J. Lanzante (NOAA/Princeton) in 1996 (International Journal of Climatology)
Multiple change-point detection

Univariate Bayesian Change-Point Analysis (Barry & Hartigan, 1993; Wang & Emerson, 2015)

→ It requires iid (Independent Identically Distributed) normal observations

This is not an issue for the sums of the ranks in the change-point detection method used here!
It addresses a lack of stationarity in a sequence of random values

Change-point: different statistical distributions before and after this point → a change in the central tendency (mean, median) and/or the dispersion (variance)

Objective identification of change-points
→ does not depend on external and/or subjective information (reference data or operator)
→ quantification ("quality" of the change-point)
The test procedure

Single change-point test (Siegel & Castellan, 1988)
Non-parametric => robust method
Resistant (= less impacted by outliers)

Multiple change-point test (Lanzante, 1996) → iterative

MBASS (Amorèse, BSSA, 2007) → derivatives

**Important caveat:** the origin of each discontinuity is not embraced by this technique (natural or change in instruments and/or data processing ?)
The test procedure

At each point $i$ in the series, the sum of the ranks ($SR_i$) from the beginning of the series to that point is computed:

$$SR_i = \sum_{j=1}^{i} R_j$$

$R(X_i) = \text{the number of } X_j's \leq X_i$

The average rank sum is:

$$\mu_{SR_i} = \frac{i(n+1)}{2}$$
The test procedure

Sum of ranks => the test is not adversely affected by outliers and can be used when there are gaps in the series

The sum of ranks is adjusted (reduction by the average rank sum):

\[ SA_i = \left| (2 \cdot SR_i) - i(n+1) \right| \]

The maximum value of the SAi values occurs at point n1 in the series
The test procedure

Adjusted sum of ranks

\[ SA_i = \left| \left( 2 \cdot SR_i \right) - i \left( n+1 \right) \right| \]
The test procedure

Next step: Wilcoxon-Mann-Whitney test for equality of medians (homogeneity of variances assumed...not mandatory for the change-point method!) → differences in the sums of the ranks before and after the \( n_1 \) point

Significance is less than 0.01=> change-point validated!

In the Multiple Change-Point analysis (Lanzante, 1996) → iterative scheme: the change-point test is applied to a series that is adjusted by subtracting from each point the median of its segment
The test procedure

Other distinctions of the Multiple Change-Point analysis → addtionnal robust rank-order test, detrending scheme & change-point signal-to-noise ratio

\[ SNR = \frac{s_D^2}{s_N^2} \]
\[ s_D^2 = \left( n_L (\bar{X}L - \bar{X})^2 + n_R (\bar{X}R - \bar{X})^2 \right) / (n_L + n_R - 1) \]
\[ \bar{X} = \frac{n_L \bar{X}L + n_R \bar{X}R}{n_L + n_R} \]
\[ s_N^2 \text{ is the noise variance (direct determination)} \]

SNR = variance due to the discontinuity/variance due to the background variability
Results

Extensometer #11

Raw data:
1 measure/5 minutes
94,583 points
From Sept. 1, 2012
To July 31, 2013
0.2mm/day

Cumulative Displacement Curve
Results - Rainfall

Each point is 3-day cumulative rainfall (rainfall cumulated over 3 days)
A single significant change-point
Location: Jan. 7, 2013
Biweight means
Before: 6.9 mm
After: 10.5 mm

P-value < 10^{-10}
Each point is 3-day cumulative displacement

3 significant change-points

Dec. 16, 2012
Feb. 3, 2013
→ 0.5mm/day
May 5, 2013

P-val $< 1.8 \times 10^{-3}$

SNR = 1.1

P-val $< 1.6 \times 10^{-9}$

P-val $< 2 \times 10^{-8}$
Interpretations

- Over a 11 months time span: **2 periods of time** for rainfall (breakpoint: Jan 7, 2013)

- **4 periods of time** for displacement values:

  The last is certainly due to incorrect measurements given by the extensometer system (beginning in May 2013)

  The larger change-point (in terms of signal-to-noise ratio) is detected on **February 3, 2013**

  ~ 1 month after the rainfall breakpoint
Conclusions and outlook

The multiple change-point method:

- provides a new hint that the landslide is not immediately impacted by rainfall (observed lag: ~1 month)

- can detect operative failures ("closing cracks")

No threshold value is arbitrarily set!

Possible implementation on a running time series, analysis of other sensors, other years, ...
References


References


