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Quantitative landslide hazard assessment at 1:250 000 scale for Malawi (Southeastern Africa)

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Landslide are ubiquitous phenomena affecting many countries around the world. In recent years, in the context of landslide risk reduction and management an increasing number of landslide susceptibility or hazard maps were carried out at the national scale. These analyses are generally based on: (1) an existing inventory (national database or compilation of work carried out individually); (2) empirical indirect or data-driven methods. However, few studies, at this scale of work, take into account the temporality of events and/or the triggering factors to assess landslide hazard assessment. This statement is often due to a lack of information, especially for emerging countries, where a lack of spatial and temporal information on events and on triggering factors subsist.

Thus, if landslide inventories provide the first information to assess susceptibility, at national scale of work, it is also necessary to identify and analyze the components inducing hazard. For instance, it is possible by different ways to complete the analyses with annual frequency of landside events and/or meteorological or seismic events to assess quantitatively the landslide hazard (Corominas et al., 2014). This identification can be carried out by (i) direct approaches based on analysis of temporal data on past landslides (e.g. computations of the exceedance probability of landslide occurrence estimated by Poisson or binomial distributions); or (ii) by indirect approaches based on analysis of triggering factors (e.g. rainfalls volume, intensity and duration).

This contribution focuses on the methodology adopted during the GEMMAP[*] project to assess landslide hazard at national scale (i.e. 1:250,000) for Malawi, a landlocked country in southeastern Africa. This country is characterized by a large diversity of landscape and a topography composed of mountains, hills and plateaus, crossed by the Great Rift Valley and the Malawi Lake. It is experiencing many slope instabilities (i.e. debris-slides, debris-flows, slides, rockslides, rock-falls), principally due to its complex geology (weathered metamorphic lithology, complex structure, active seismic activity) and intense rainfalls (from tropical cyclones to depressions, World Meteorological Organization, WMO, <https://public.wmo.int/en>).

The methodology is split in four steps following the JTC-1 guidelines following the Eq. 1, either:

$$P(S) \times P(St) \times P(Me) = P(H) \quad (\text{Eq. 1})$$

Where $P(S)$ = spatial probability to have landslide (based on spatial modelling); $P(St)$ = exceedance probability to have more than one landslide for one type meteorological event for an interval time (based on Poisson probability model); $P(Me)$ = exceedance probability to

have more than one climatic event an interval time (based on Poisson probability model); P (H) = hazard probability.

- i. The first step is based on an improvement of the landslide inventory by visual remote sensing and field surveys. A database was performed integrating information on the type of slope instability, activity, and triggering periods (Thiery et al., 2019).
- ii. The second step consisted to assess and map landslide susceptibility by a data driven method for each type of selected landslide. The method used is based on Bayes' theorem (Weight of Evidence, Bonham-Carter, 1994) computing the spatial probability for each debris-slides, debris-flows, and slides (i.e. rotational and translational slides). A sensitivity analysis about spatial variables and their resolution was performed as well as statistical tests to validate results following the procedure described in Thiery et al. (2007). Once the best spatial variables selected 4 classes of susceptibility are retained (negligible, low, moderate, high) inspiring by the JTC-1 guidelines. This step corresponds to the first term of the equation 1 (P(S)).
- iii. The third step focused on the temporal analyses of the events taking into account: (1) the rainfall recurrences time induced by different types of tropical meteorological events between 1946 and 2019 (n=28; World Meteorological Organization; P(Me) Eq. 1), (2) the recurrence time for the different landslide types for the same period (P(St) Eq. 1). Because cyclonic events are based on wind velocity, (Meteo-France classification WMO) no rainfall data were collected for Malawi. However, rainfall amounts and intensities are considered to be correlated with the strength of tropical cyclones (WMO), thus, it is considered that the more intense the cyclone, the heavier and more intense the rainfall. This analysis has led to compute the exceedance probability (i.e. based on Poisson distribution, Crovelli, 2000; Guzzetti et al., 2006) for:(1) each type of meteorological events and (2) each type of landslide for each susceptibility class for each type of meteorological event.
- iv. The temporal probabilities were integrated to the landslide susceptibility maps by a matrix approach in order to obtain hazard maps for different landslides triggered by different meteorological events. Thus for each phenomenon, six hazard maps were obtained for six return periods from 1 to 100 years (1, 5, 10, 25, 50 and 100 years; Fig. 1).

The results obtained through this method allow establishing national hazard scenarios for the six return periods and for different type meteorological events and landslides (Fig.1). Furthermore, the approach being flexible, it allows modifying easily the hazard maps if new temporal information about landslides or meteorological events are integrated.

[] The "Geological Mapping and Mineral Assessment of Malawi" project is led by the BRGM, with international partners: GTK (Geological Survey of Finland), and CGS (Geological Survey of South Africa) for the Government of Malawi through the Geological Survey Department (GSD).*

$$P(S) \times P(St) \times P(Me) = P(H)$$

$P(S)$ = spatial probability to have landslide (based on spatial modelling)
 $P(St)$ = exceedance probability to have more than one landslide for one type meteorological event for an interval time (based on Poisson probability model)
 $P(Me)$ = exceedance probability to have more than one climatic event an interval time (based on Poisson probability model)

Identification of major climatic events for the country (Classification Meteo France) since 1946

Event	n
4. Severe tropical cyclone	1
5. Tropical cyclone	2
6. Intense tropical cyclone	3
7. Very intense tropical cyclone	3



$P(St)$

Temporal exceedance probability of event for one meteorological event (Cat. 7 - ref time = 73 yr)

	Time interval (yr)					
	1	5	10	25	50	100
S1	1.81E-05	9.03E-05	1.81E-04	4.51E-04	9.02E-04	1.80E-03
S2	3.97E-04	1.98E-03	3.96E-03	9.88E-03	1.97E-02	3.99E-02
S3	1.01E-03	5.02E-03	1.00E-02	2.49E-02	4.91E-02	9.58E-02
S4	2.91E-03	1.46E-02	2.87E-02	7.03E-02	1.38E-01	2.53E-01

$P(Me)$

Temporal exceedance probability of specific meteorological event (cat. 7 - ref time = 73 yr)

Type of Me	Time interval (yr)					
	1	5	10	25	50	100
Cat. 7	4.03E-02	1.86E-01	3.37E-01	6.42E-01	8.72E-01	9.84E-01

$P(H)$

	Time interval (yr)					
	1	5	10	25	50	100
S1	7.27E-07	1.68E-05	6.08E-05	2.90E-04	7.87E-04	1.77E-03
S2	1.80E-05	3.68E-04	1.34E-03	6.34E-03	1.71E-02	3.83E-02
S3	4.05E-05	9.33E-04	3.38E-03	1.60E-02	4.28E-02	9.42E-02
S4	1.17E-04	2.69E-03	9.68E-03	4.51E-02	1.18E-01	2.49E-01

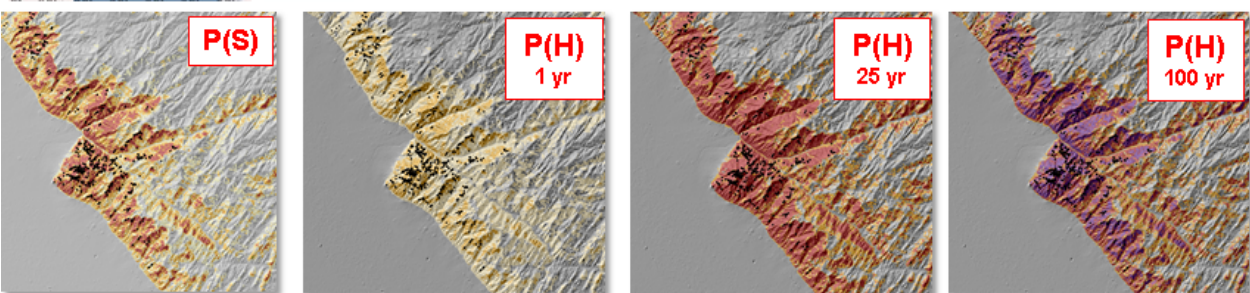


Figure 1. Rationale of the methodology to obtain national landslide hazard maps at 1:250 000 scale for Malawi (adapted from Thiery et al., 2021).

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