Why landslide susceptibility maps should change over time

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Abstract

Landslide susceptibility map (LSM) is a key element in hazard mitigation, risk management and regional planning. In mountainous area, hazard prediction, disaster prevention, mitigation strategies, crisis and risk management , and proper land use planning need reliable and accurate landslide susceptibility mapping.

We got inspired when we looked at spatial association and overlap between landslides in a multi-temporal landslide inventory from Collazzone area in central Italy. Then, we came up with a hypothesis so called “landslides cause landslides” where we used path dependency and self-organization concepts from complex system theory to explain our hypothesis. Applied to landsliding, Path dependency means that the future state of landsliding system depends in the history of landslide activities.

We studied these indications of path dependency and self-organization in occurrence of landslides using the multi-temporal landslide inventory containing 17 time slices of mapped landslides. We define follow-up landslides based on spatial association between landslides in the multi-temporal landslide inventory. Follow-up landslides could be either completely inside, partly overlap or touch landslides in an earlier time slice. Locations that have experienced landslides, appear to be more susceptible to occurrence of follow-up landslides with a gradual decrease over time. Our quantification of landslide path dependency indicates an exponential decay behaviour in which increased susceptibility caused by earlier landslides is reduced to about a quarter of its magnitude after ten years, and is insignificant after ~25 years. The importance of path dependency is illustrated by the fact that follow-up landslides are larger than non-follow-up landslides. Also, follow-up landslides are more elongated than follow-up landslides and have different power law scaling behaviours.

We subsequently investigated which landslide geometric and topographic attributes can explain which landslides experience follow-up landsliding. Results of ANOVA analysis showed that landslide geometric attributes (size and shape) are strong diagnostic criteria determining whether a follow-up landslide happens. Additionally, the mean value of topographic wetness index (TWI), vertical distance to channel network and relative slope position were all statistically significant ($p < 0.05$) where earlier landslides caused follow-up landslides, and hence should be considered in prediction of landslide occurrence.

We then predicted whether landslides would experience follow-up landslide, based on these findings, using logistic regression. A model that only used geometric landslide attribute (size) was able to predict the occurrence of follow-up landslides (53%) better than a model where only topographic attributes were used (52%). Landslide geometries and topographic attributes together predicted whether a landslide will experience a follow-up landslide, with about 60% confidence. Adding land use and geology to the models did not change the validity of predictions.

Our results suggest that temporal landslide path dependency plays an important role in the long-term evolutionary process of landslides. Where a landslide affects a slope strongly, follow-up landslides are likely to occur and eventually, in the study area. Over time, clusters of follow-up landslides may form. In our study area, the path dependency between landslides contributed to the development of 444 clusters of landslides, containing 2350 landslides (77% of the total number of landslides). The largest cluster consisted of 55 landslides which were recorded in 12 time slices. 738 landslides did not (yet) experience follow-up landslide. There is an exponential growth behaviour between the size of first landslide hit the hillslope and the number of landslides in the cluster.

It is tempting to contemplate a simple modification to existing susceptibility modelling approaches that honours these findings. This modification would temporarily raise (or, in other geomorphic settings, lower) the landslide susceptibility after a landslide occurs. Our findings show that we can quantify both the characteristic time-scale and the relative increase in susceptibility based on a multi-temporal landslide inventory. Traditionally, landslide susceptibility is considered as a time-invariant function of conditioning attributes (e.g. geology and slope). Our indication of path dependency is particularly surprising because it contradicts this traditional model. The path dependency in landsliding suggests a time-variant susceptibility affected by the spatial and temporal legacy effects of earlier landslides. Based on that, we propose a time-variant landslide susceptibility model in which landslide susceptibility is a function of conditioning attributes (e.g. slope and lithology) and the history of landslide activities (path dependency). We also stress the mapping and documenting of landslides based on multi-temporal landslide inventory in which landslides are mapped in polygon format. With this, we would be able to monitor the rate of activities of landslides overtime. Regular updated time-variant landslide susceptibility map has implication in regional planning and management of hazards and risks resulted from landslide occurrence.