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Assessment methodology for the prediction of landslide dam hazard

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Abstract

This paper represents a contribution to the study of hazard caused by the interaction between landslides and river courses. The effects of such interferences are often catastrophic and could include the formation of backwater lakes, potential dam failure, river bed dynamics and morphological alterations. These scenarios could be substantially reduced if it was possible to predict the eventuality that a moving landslide could block the river. This is a complex topic because it involves composite geomorphic phenomena concerning both hillslope and river systems and their interpretation, through model approaches, is still under development and testing. In this study, a methodology developed in the framework of the European Research Project IMPRINTS (FP7), was adopted and integrated in order to identify the areas of triggering and propagation of landslides and to characterize the possible scenarios of the interaction with river networks. Different deterministic and probabilistic approaches, calibrated using a case test in the middle valley of Noce River in Basilicata region (Italy), were applied and compared at basin scale. In this area, a landslide mobilized in July 2007 on the right side slope of the river invaded a gravel-bed reach, characterized by a narrow and confined section, causing its progressive morpho-hydrodynamic change.

1 Introduction

The interference between landslide and river courses is a topic of great relevance, because to date many catastrophic events have occurred in the world as a consequence of breaching of dams produced by landslides (Costa and Schuster, 1988). Damming the river may cause the formation of upstream backwater, natural dam evolution, upstream and downstream flooding, initiation of other landslides and debris flows, river bed dynamics and channel instability (Swanson et al., 1985; Casagli and Ermini, 1999; Schuster, 2000).

The interpretation of these phenomena is a complex topic, because of the numerous variables involving both hillslope and river dynamics at the same time. The phenomenon, though well studied, is still not consolidated into an accredited theory and is particularly suited to the development of scientific research, especially in the modeling field because the hydrodynamic interference between landslides and rivers and the dam creation has not been sufficiently studied.

The main purpose of the literary analysis is to forecast the main scenarios connected with a damming episode. These studies take into account the landslide dam inventory that represents the fundamental tool for the identification of the role played by hillslope and river systems. Most of them refers to database of damming episodes that have occurred wordwide (Costa and Schuster, 1991) and primarily in the Italian territory (Casagli and Ermini, 1999; Crosta et al., 2004; Nicoletti and Parise, 2002).

The study of the possibility that a moving landslide could block a river can be reached starting from quantitative assessments of landslide hazard that usually employ empirical, heuristic, deterministic, or statistical approaches (Korup, 2005). With reference to the dam creation, several authors, using a dataset of landslide dam phenomena distributed worldwide, proposed some geomorphic indexes to forecast landslide dam behavior which take in account mainly geomorphic variables characterizing both the landslide and the river channel. Currently, the geomorphic approach is widely used also to predict dam evolution from the combination of variables identifying both dam and river (Swanson et al., 1986; Costa and Schuster, 1988; Casagli and Ermini, 1999; Ermini and Casagli, 2003; Korup, 2004). Moreover, the flood hazard related to the failure of natural dams is generally analyzed through deterministic models that simulate the dam break and estimate the hydrographs resulting from dam failures (Davies et al., 2007; Fread, 1991).

The objective of this study is to assess a methodology to predict the possibility that moving landslides could block a river, using different and more complex methods from empirical approaches to dynamic ones. The models, calibrated in a case study on the

Noce river in the Basilicata region (Italy), was applied at the basin scale allowing to assess preliminary and final hazard maps of landslide dams in the study catchment.

2 Case study

The case study is the interaction between a landslide and a narrow gravel-bed reach in the middle valley of the Noce River (total catchment area 413 km^2), located in the Trecchina territory in SW Basilicata (Fig. 1a, b). The landslide, named the Zillona, mobilized along the right side slope of the basin (Fig. 2a) and produced the partial and then the total blockage (respectively July 2007 and November 2007) of the water course, for 120 m of its length, with the formation of a little backwater lake upstream (Fig. 2b). The floods avoided the landslide bottom, producing an avulsion with the incision of a bend on the left floodplain, thus favoring the dam emptying process (Fig. 2c). The combined effects produced a new river morphological configuration with a progressive lowering of the floodplain (Fig. 3a, b). This highlighted cyclopean boulders next to the outside bank of the bend, probably belonging to an ancient mass movement in the left side of the hillslope (Fig. 3c). The landslide interference induced morpho-hydrodynamic changes also in the upstream and downstream reaches, because of the flow slowdown and deposition of sediments coming from upstream, forming bar sequences and armoring bed structures.

2.1 Geological setting

The Zillona landslide is located in western side of Parrutta spring and to south the Trecchina town. The study area is characterized by a complex geological and structural setting. In this area outcrop carbonate deposits related to the M. Bulgheria Verbicaro and Alburno Cervati Units and blackish siliceous marls and argillites from the Liguride Unit (Fig. 3c). The structural relationship between these geological formations consists of the overthrusting of the M. Bulgheria Verbicaro Unit on the Liguride Unit and of the last one on the Alburno Cervati Unit (Cotecchia et al., 1990). The Bulgheria Verbicaro Unit (Jurassic) is constituted by a carbonate succession of dolomitic limestone and dolomites at the base passing upward into an alternation of the limestones, calcilutites and calcarenites formations. These lithologies are located in the western part of the studied area, on the upper part of the right side of the Noce valley. The Alburno Cervati Unit (Cretaceous) is composed of a carbonate platform complex too, similar to the previous and is located in the high slope of the left side of Noce river. All these geological formations are well stratified and intensely deformed and fractured. The Liguride Unit (Cretaceous-Lower Eocene) consists primarily of Flysch complex, formed of marly-clayeyand showing generally a disorganized structure due to the intense tectonic processes that have affected this portion of the chain. This geological formation characterizes primarily the Zillona landslide on the lower right slope of Noce river. The original structural arrangements of the units described have been modified by tectonic transcurrent movements along the Pollino line during the Pleistocene. The Parrutta area is the result of these geomorphic activities and has the characteristics of a small basin type pull-apart, tectonic depression oriented in NS direction, bordered by faults with predominantly vertical component.

2.2 Zillona landslide geomorphology

The slope studied is widely interested by the geomorphological effects of an intense morpho-gravitational dynamics characterized by the large and complex mass movements and the deep seated gravitational phenomena (DGPV). These phenomena are located in the upper portion of the slope and consist of widely and deeply lateral spreading involving the large blocks of limestone-marl (Bulgheria – Verbicaro Unit), disarranged and basculating. The landslide studied involves the southern edge of this area of gravity deformation (Cotecchia et al., 1990). The Zillona landslide is an ancient, complex and still active rototranslational slide evolving into a large earthflow in 2007 (Cruden and Varnes, 1996; Di Maio et al., 2009). This landslide, which involves “Crete Nere” formation from Liguride Unit, is approximately 650 m long, from 130 to 160 m

wide, extends between 275 and 130 m a.s.l. (Noce river) and the medium inclination is about of 13°. Accurate in situ geological and geomorphological survey, aerial photos analysis and interpretation of geognostic data related to eleven boreholes performed throughout the landslide body made it possible to define the main geomorphological features and state of activity of the landslide and particularly in its three different areas (source area, flow channel and accumulation area). The collected information together with the results coming from the new geomorphological survey, allows us to obtain a better definition of the geological and geomorphological features of the landslide; some reconstructions are shown in Fig. 4. Along the main body of the landslide there are several secondary scarps, morphological depressions, surface land sliding, a wide counter-sloping landslide terraces can be observed and creeping evidences.

The source area of the large earthflow is referable to a multiple and retrogressive rototranslational slide, largely emptied and actually showing a concave shape. The main scarp, at an elevation of about 300 m a.s.l., shows a semicircular shape and it is involved in rockfalls and small rockslides. The source area is almost entirely covered by debris deposits of disjointed limestone and marl blocks immersed in a fine-grained matrix. In the eastern part of the source zone long and narrow debris flow is nowadays very active East of the source zone, a long and narrow debris flow is nowadays very active . The flow channel, which is probably placed an a preexisting drainage line, extends between the 275 and 140 m a.s.l. and has mean inclination of 13°. It is long about 545 m and the width varies between 110 m and 140 m. It is delimited by two evident flanks. The accumulation zone shows a typical fan shape with a mean inclination of 6°. It is about 100 m long and 120 m width. The landslide toe is located in the bed of Noce River. At present time some evidences of activities are quite visible in the same areas involved in the reactivation of 2007.

3 Methodological approach

A methodology, developed in the framework of IMPRINTS – IMproving Preparedness and RIsk maNagemenT for flash floods and debriS flow events – FP7 (Bregoli et al., 2010), was integrated in order to identify possible river network areas affected by landslide dams. This is a multilevel method, consisting in a basic and an advanced level, that uses more complex models to identify landslide dams and potential scenarios through geometrical and dynamic approaches (Fig. 5). The methodology is composed of three phases of investigation:

1. estimation of the volume potentially mobilized by a given value of precipitation with an assigned return period (initiation models: deterministic approach);
2. definition of the invasion areas and of the resulting energy (propagation and deposition models: stochastic and numerical models);
3. definition of landslide-river interference scenarios (deterministic approach: geomorphic indexes).

3.1 Initiation models

In this study, SHALSTAB method (Montgomery et al., 1994), resulting from the combination of a slope stability model and a hydrological model, was applied in each level of the methodology only to assess shallow-landslide susceptibility in the catchment.

The model is based on the hypothesis that the steady-state conditions are reached after a rainfall having constant intensity and indefinite duration. Assuming the complete saturated material, the relation between rainfall and soil transmissivity may be derived for every cell of the DEM, as the result of the following expression:

$$\frac{q}{T} = \frac{\sin\alpha}{(a/b)}\left(\left(\frac{c'}{\rho_\mathrm{w} g z \cos^2\alpha \tan\phi}\right) + \left(\frac{\rho_\mathrm{s}}{\rho_\mathrm{w}}\right)\left(1 - \frac{\tan\alpha}{\tan\phi}\right)\right) \tag{1}$$

in which q is the rainfall intensity, T is the soil transmissivity, α is the slope, a/b is the cumulated area per unit of flow, ρ_w is the density of water, z is the thickness of soil, c' is the soil cohesion, φ is the soil internal friction angle and ρ_s is the saturated bulk density of the soil. Hence the safety factor F_s may be then computed as follows:

$$F_\mathrm{s} = \frac{c' + z\gamma_\mathrm{w}\cos^2\alpha - \tan\phi}{z\gamma_\mathrm{s}\sin\alpha\cos\alpha} - \frac{\gamma_\mathrm{w}}{\gamma_\mathrm{s}}\frac{\tan\phi}{\tan\alpha}\left(\frac{h}{z}\right) \tag{2}$$

in which γ_s is the specific weight of saturated soil and γ_w is the specific weight of water.

In this study, the duration of the rainfall event were fixed equal to the time necessary for the soil to reach a steady state condition through the following relation (Papa et al., 2010):

$$\tau_\mathrm{s} = \frac{1}{n}\sum_{i=1}^{n}\frac{a_i}{b_i}\frac{\theta_{\mathrm{s}_i}}{K_i\cos\alpha_i\sin\alpha_i} \tag{3}$$

in which n is the basin cell number, τ_s is the time for saturation and θ_s is the water content at saturation.

The rainfall intensity, corresponding to the duration time of rainfall (τ_s) for the different return periods, is derivable by the Intensity-Duration-Frequency curves.

3.2 Propagation and deposition models

At the basin scale, the results achieved with the application of models for stability are needed to delimitate landslide runout areas.

The first level of the methodology is a geometrical approach, useful for a preliminary evaluation of landslide-river interaction areas. Dfwalk model (Gamma, 1999; Hurlimann et al., 2008) that integrates D8 flow routing method (O'Callaghan and Mark, 1984) with the random walk theory (Montecarlo) and the empirical model "reach angle" that includes correlations of travel angle and volume (Corominas, 1996), was adopted. The first is used to determine the preferential flow path, and the last is used to define the landslide runout.

The probability, P_{xy} was computed for each cell of the DEM using the following equation:

$$P_{xy} = \frac{n_{\text{afect}}}{n_{\text{iter}}} \tag{4}$$

in which n_{afect} is the number of flow trajectories that invaded a cell and n_{iter} is the flow trajectories calculated.

The second level, advanced, was assessed to study the process of interference in dynamic terms, quantifying the parameters of depth and velocity of the mass movement as well as the hydrodynamic parameters of the river flow.

In the first approach of this level, dfwalk model was combined with the rheological model for the propagation of landslides, estimating the velocity in interaction cells and assuming constant thickness.

The rheological approach used in the study for the interpretation of landslide mobility was the Coulomb-Viscous model that is widely recognized (Coussot, 1997) as one of the most well developed models for describing viscoplastic material properties in laminar regimes (Johnson, 1970):

$$\tau = \tau_0 + (\sigma - u)\tan\phi + \eta\left(\frac{\delta v}{\delta z}\right)^n \tag{5}$$

in which σ is the effective normal stress, u is the water pressure, φ is the friction angle, η is the dynamic viscosity of matrix, y is the depth normal to flow surface and n is the exponent.

In order to calculate the velocity deposition of the landslide, the energy equation was used:

$$E_{\text{cin}} + E_{\text{pot}} = \text{cte} - \Delta E \tag{6}$$

in which E_{cin} is the kinetic energy per unit area, E_{pot} is the potential energy per unit area, ΔE is the energy losses per unit area and cte is the costant.

The second approach was the most complex method and was performed by a two dimensional finite volume code FlatModel (Medina et al., 2008). The model, starting from an estimate of the rheological properties of the materials involved and using the De Saint Venant conservation equations of motion, allowed us to have quantitative information for velocity and thickness of landslide deposition cells. The necessary information included two raster data sets with a detailed DEM and a raster map defining the initial extension and volume of the landslide.

3.3 Landslide and river interference approaches

The possibility that a moving landslide could block a river depends on many geomorphic factors that involve both landslide and river dynamics at the same time. The prediction of these scenarios could be reached through deterministic approaches, by the formulation of geomorphic indexes which take into account mainly geomorphic variables of both river and landslide (Table 1). These parameters are generally correlated to the landslide velocity and the channel width (Annual Constriction Ratio, Swanson et al., 1985, 1986), to the dimension of the moving mass and the river water discharge (Dimensionless Flow Index, Ermini and Casagli, 2003) and to the grain size and texture of the blockage material (Dimensionless Constriction Index, Ermini, 2003).

In this paper, a new geomorphic index, Dimensionless Morpho-Invasion Index (DMI), was proposed and applied, as the result of the following expression:

$$\text{DMI} = \frac{\text{Landslide momentum}}{\text{River momentum}} = \frac{m_\text{s} \cdot U_\text{s}}{F_\text{w} \cdot t} = \frac{2 \cdot \rho_\text{s} \cdot U_\text{s}^2 \cdot V_\text{s}}{\rho_\text{w} \cdot g \cdot h^2 \cdot B_\text{w} \cdot W} \tag{7}$$

in which ρ_s is material density of the landslide; V_s is the landslide volume; ρ_w is the water density; g is the gravity acceleration; h is the hydraulic level.

This approach extends the physical parameters to consider in the complex description of the phenomenon allowing us to characterize with more accuracy the possible scenarios due to the interference between landslide and river network. The index expression uses the momentum of both landslide and river, including variables referred to the geometric, kinematic and dynamic characteristics of two systems at the same time.

In this application, it was assumed that, for values of the dimensionless parameter DMI > 1, there was a phenomenon of total occlusion with a consequent formation of a landslide dam. This is a preliminary hypothesis that should be tested with a database of landslide dam events.

4 Application and results

4.1 Triggering

The methodology described was applied to the Noce river basin. The catchment (DEM 20 × 20 m) was studied in the hydrological behavior and discretized into homogeneous areas according to the hydro-geological characteristics (Fig. 6a). The safety factor F_s was computed for each return period (T_r =10, 100, 500 yr) corresponding respectively to high, medium, and low hazard (Guzzetti, 1999; Carrara, 2008). The results (Fig. 6b) were evaluated comparing the SHALSTAB slope instability map with the location of landslide areas surveyed on the field (PAI, 2010).

4.2 Back analysis

In the geometrical level of the methodology, dfwalk model was applied in combination with the empirical relationship (Corominas, 1996), calibrating geometrical parameters in order to obtain the most correct runout distance ($V = 4.5 \times 10^5\,\mathrm{m}^3$, $H/L_{\max} = 0.24$ rad):

$$\tan\beta = H/L_{\max} = 0.97V^{-0.105} \tag{8}$$

in which β is the reach angle, H is the vertical drop, $L_{\max}$ is the horizontal projection of the total runout distance and V is the landslide volume.

In the dynamic level, numerical models (dfwalk model and FlatModel) were implemented adopting, as rheological properties of material entrainment (clay-marls), the back-analysis results of the landslide which occurred in 1997 in the Noce river basin (Fig. 7). In the Coulomb-Viscous model, it was assumed that the yield stress is $\tau_y = 9$ kPa, the dynamic viscosity is $\eta = 0.7$ kPas and the unit weight is $\gamma = 18.0\,\mathrm{kN\,m}^{-3}$.

4.3 Propagation

Geometrical and dynamic approaches were applied at basin scale, as part of the clay-marl geological formations, in order to identify runout areas (Fig. 8a, b; Fig. 9a, b). The cells of landslide triggering are those classified as high hazard ($T_r = 10$ yr) with SHALSTAB model, considering a thickness of 4 m according to the landslide main scarp studied. In order to improve the quality of the DEM in the valley areas, that is in the zones of possible interaction between water course and hillslopes, it was modified, for a width of approximately 500 m, through the use of the photogrammetric relief in 1 : 5000 scale. The results demonstrate that the use of dfwalk model overestimates runout areas compared to the 2-D numerical FlatModel, and can be used as a precautionary approach useful to obtain preliminary hazard maps (Fig. 10).

4.4 Landslide-river interference

In order to define, along river networks, the areas in which a partial or total blockage of the river was possible, the raster maps of hydrodynamic ($Q_T = 5_{\text{years}}$, $h_T = 5_{\text{years}}$) and morphological parameters (B_w) were calculated using respectively VAPI method (Gioia et al., 2008) and morphological classification. Runout areas of earth flows and river networks were overlayed in GIS (Geographic Information System) and the different geomorphic indexes were calculated in the interaction grid cells.

The application shows that is possible to define potential landslide and river interaction areas with more complexity depending on the method use, from geometrical to dynamic ones. The spatial localization of the possible landslide dam in the catchment, evaluated with the different models, was almost in agreement and was observable mainly where the river network was narrow and confined. However the use of dfwalk model, representing the spatial probability that a cell of the river network will be invaded by a landslide and considering the hypothesis of invariability of landslide depth along the distance travelled, can only establish a preliminary evaluation of landslide dam hazard (Figs. 11a, 12a, 13a, 14a). The maps constructed using 2-D numerical modeling (Figs. 11b, 12b, 13b, 14b) diverge from those created with dfwalk modeling because of the extension of the hazard zone, which is smaller (Table 2). This method should be applied to establish a detailed final hazard analysis. In both cases, the results obtained demonstrated that an accurate digital elevation model is fundamental to obtain better runout results. The topographic information, as well as the rheologic parameters used in the runout analysis, influence the flow trajectories of landslide and significantly affects their deposition in the valley areas.

The analysis of the landslide dam scenarios, evaluated with deterministic approaches, can be sensible with the choice of the geomorphic index applied. The results show that a detailed mapping of landslide dam hazard, with indication of incomplete damming episodes, can be achieved with an extensive characterization of the landslide and river systems that take into account more parameters, such as the volume and grain characteristic of the landslide and the stream energy, expressed in terms of the river discharge or momentum.

5 Conclusions

Landslide dam hazard is a very complex topic because it involves composite geomorphic phenomena concerning both landslide and river systems. In this study, a methodology assessed in the European Research Project IMPRINTS (FP7), appropriately integrated with the use of geomorphic indexes, is applied in a case study in order to assess preliminary and final hazard maps of landslide dams in a river basin. Dfwalk model, calibrated using the empirical and Coulomb-Viscous rheological approaches, allowed a more plausible interpretation of the landslide studied. At the basin scale, the use of dfwalk model in the homogeneous geological areas overestimates runout areas compared to the 2-D numerical model FlatModel, proving to be a precautionary approach useful to obtain preliminary hazard maps. However, much work remains in calibrating these models particularly to facilitate a reliable choice of the rheology of material entrainment. Concerning the issue of forecasting the possibilities of a landslide to block a river channel, the final results demonstrates that it is possible to have a prediction of a landslide dam with a more defined accuracy depending on available data, using the geometrical or dynamic approaches. The spatial localization of the possible landslide dam in the catchment is almost in agreement, while landslide dam scenarios can be sensitive to the geomorphic index applied. The geomorphic index DMI proposed, describing the interference between river network and slopes, interfaces and integrates effectively with the models used for the identification of areas of propagation because it includes the kinematic parameters as well as the geometry of the moving mass. This approach, after a preliminary validation phase using a database of landslide dams, can be a useful tool in the decision making processes associated to the forecast of dam creation and management of emergencies deriving from these events.

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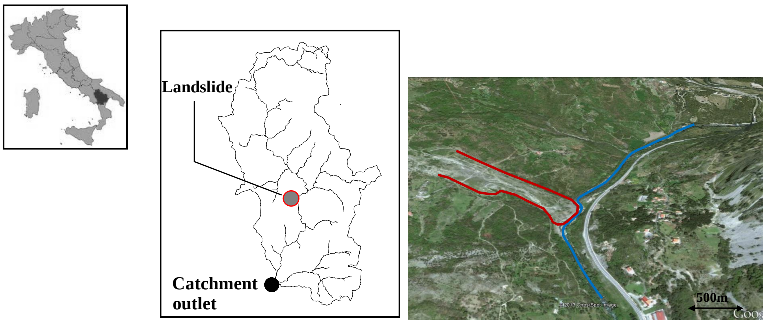
Table 1. Main geomorphic indexes of landslide-river interference in literature.

Author	Formula	Condition of blockage
Swanson et al. (1985, 1986)	$\mathrm{ACR} = \frac{U_\mathrm{s}}{B_\mathrm{w}}$	$\mathrm{ACR} > 100$
Ermini e Casagli (2003)	$\mathrm{DFI} = \frac{U_\mathrm{s} \cdot W \cdot D}{Q_{T=5}}$	$\mathrm{DFI} > 1$
Ermini (2003)	$\mathrm{DCI} = \frac{U_\mathrm{s} \cdot W \cdot D \cdot d_{30}}{Q_{T=5} \cdot B_\mathrm{w}}$	$\mathrm{DCI} > 0.002$

U_s, landslide average velocity; W landslide width; D landslide depth; B_w, river width; $Q_{T=5}$ discharge at 5 yr return period; d_{30} 30° percentile of the cumulate grain size distribution.

Table 2. Summary of results using different models and methods.

Model	Method	Runout area (km^2)	Interaction areas (km^2)
dfwalk	Empirical: Reach-angle	25.7	0.15
	Rheological: Coulomb-Viscous	29.3	0.13
FlatModel	Rheological: Coulomb-Viscous	19.5	0.08



(a)

(b)

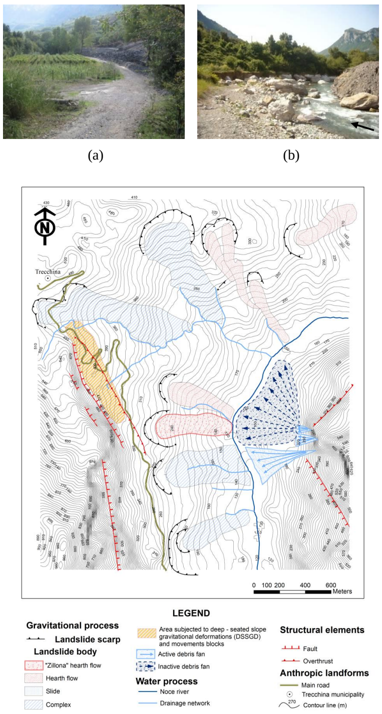
Fig. 1. (a) Study catchment and landslide location. **(b)** 3-D view of the landslide-river interference.

(a)

(b)

(c)

Fig. 2. (a) Landslide body. **(b)** Backwater lake upstream. **(c)** Dam emptying process.



(a) (b)

(c)

Fig. 3. Floodplain in the 2007 pre-landslide **(a)** and post-landslide **(b)** phases. **(c)** Geomorphological map of the Parrutta area.

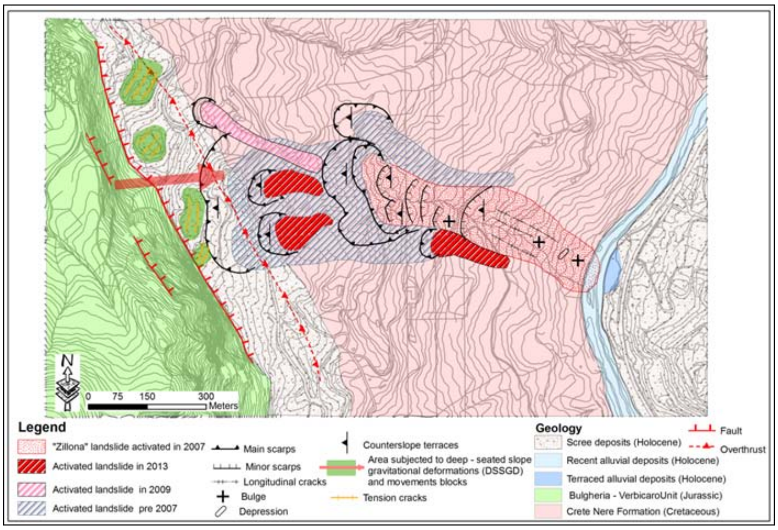


Fig. 4. Geomorphological map of the Zillona landslide.

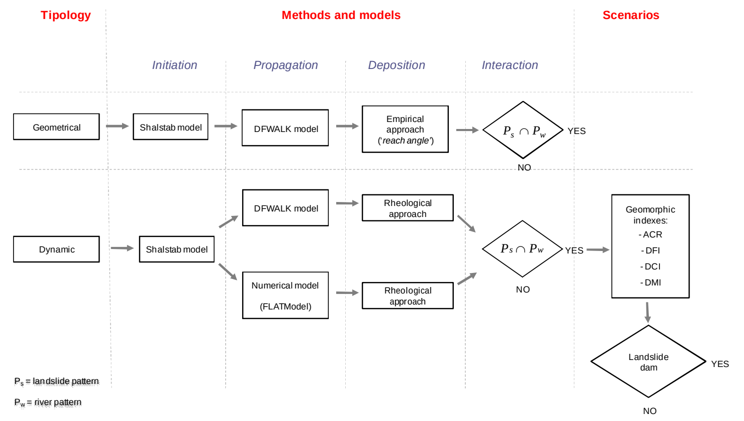
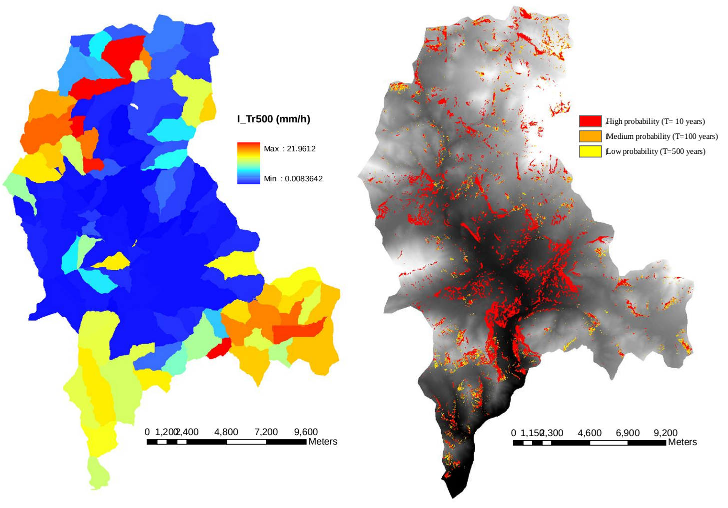


Fig. 5. Hazard assessment methodology of landslide-river interference.



a) b)

Fig. 6. (a) Example of rainfall intensity (T_r = 500 yr). **(b)** SHALSTAB simulation results.

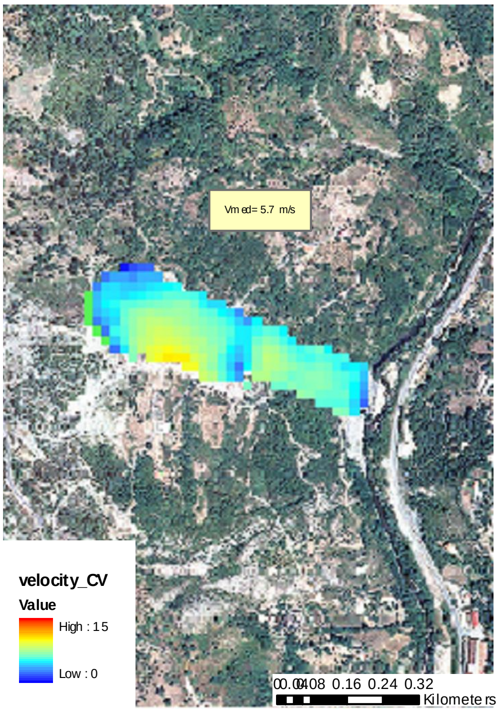
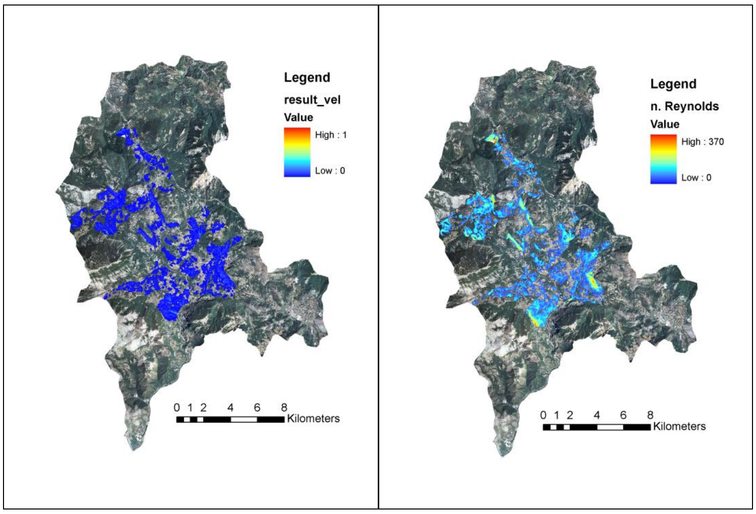
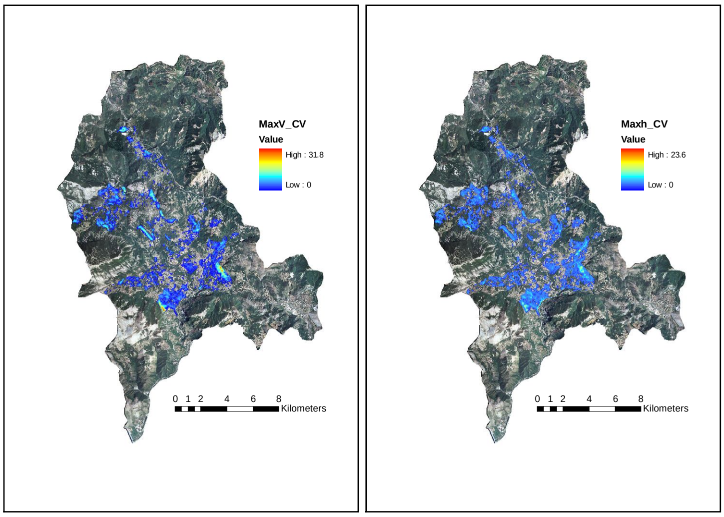


Fig. 7. Back analysis of the 1997 earth-flow using dfwalk model and rheological approach.



(a) (b)

Fig. 8. Runout map **(a)** and Reynolds number calculation **(b)** using dfwalk model.



(a) (b)

Fig. 9. Runout map with indication of velocity **(a)** and max depth **(b)** using FlatModel.

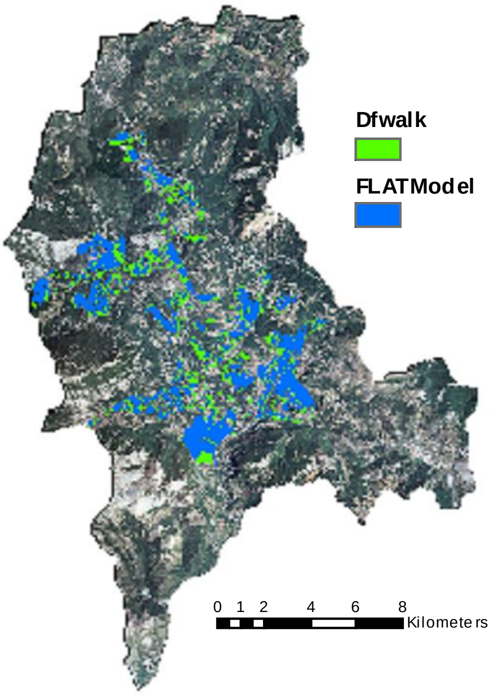
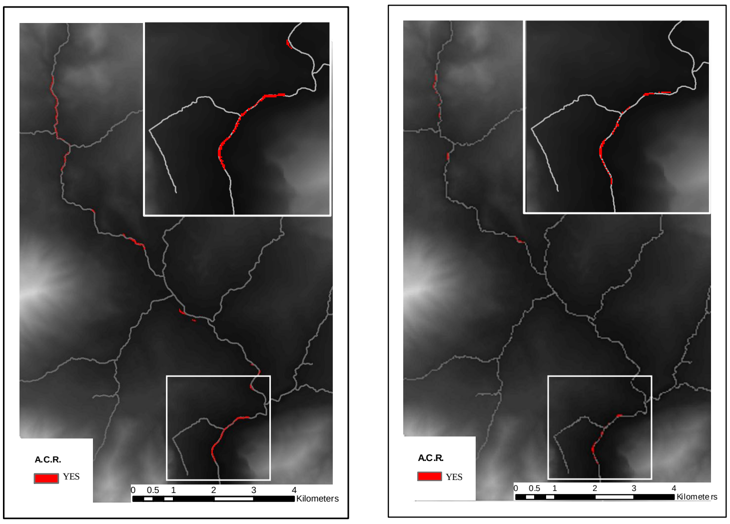
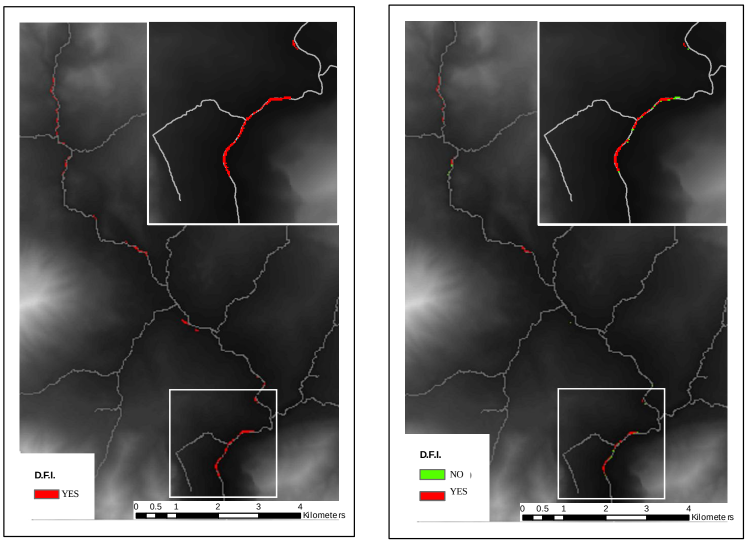


Fig. 10. Comparison of runout areas between dfwalk model and FlatModel.



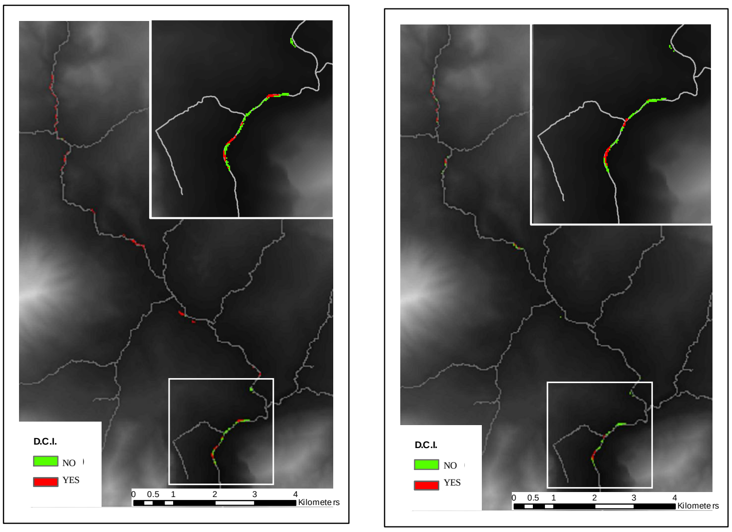
(a) (b)

Fig. 11. Indication of the possible areas of partial (green) and total (red) river blockage according to the geomorphic index ACR using dfwalk model **(a)** and FlatModel **(b)**.



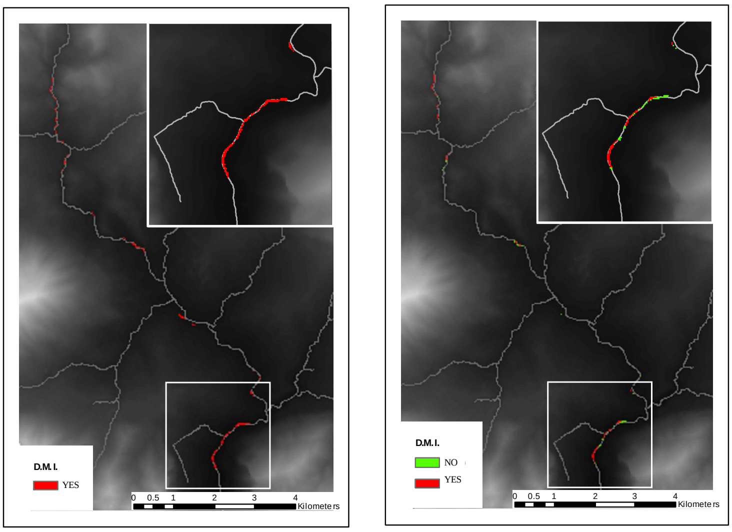
(a) (b)

Fig. 12. Indication of the possible areas of partial (green) and total (red) river blockage according to the geomorphic index DFI using dfwalk model **(a)** and FlatModel **(b)**.



(a) (b)

Fig. 13. Indication of the possible areas of partial (green) and total (red) river blockage according to the geomorphic index DCI using dfwalk model **(a)** and FlatModel **(b)**.



(a) (b)

Fig. 14. Indication of the possible areas of partial (green) and total (red) river blockage according to the geomorphic index DMI using dfwalk model **(a)** and FlatModel **(b)**.