# Damming Predisposition of River Networks: A Mapping Methodology

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## Abstract

Landslide dams may collapse within few hours/days after their formation resulting in destructive flooding wave. Due to the limited time available since their formation, forecasting tools able to assess the damming susceptibility over large areas are more advisable for prevention and setting up mitigation measures. A semi-automated GIS-based methodology is proposed in this work to map the spatial damming predisposition over large areas, to analyse consequence and risk scenarios. The procedure is based on a morphological index that use a statistical correlation between morphometric parameters to spatially assess the chance of a river obstruction through the reactivation of an existing landslide. This damming mechanism were tested on the Arno River basin (9116 km$^2$) in Italy, where about 30,000 landslides are mapped. The highest mountain ridges in the Eastern part of the area resulted as the most susceptible to damming in the basin. The concentration of the historical landslide dams endorses the results for this basin.

## Keywords

Landslide dams • Susceptibility • Natural hazards • GIS

## Introduction

River obstructions are common geomorphologic processes in mountain regions and can cause serious hazards such as upstream backwater, catastrophic flooding, riverbed modification and channel instability (whit possible secondary landslides) (Costa and Schuster 1988; Casagli and Ermini 1999). The consequences of landslide dams may have substantial economic, social and environmental impacts in valley floors, where human activities most concentrated. It is widely documented (Ermini and Casagli 2003; Tacconi et al. 2015) that most of landslide dams have a short life, as about 40% of them fail within 24 h after their formation and less than 20% last more than one month. The available time is often not enough for a reliable stability analysis and only techniques requiring rapid data collection can be used. Planning and prevention measures (e.g. risk mapping) are essential to reduce natural hazard consequences where the expected damming probability is high.

Ancient landslides, dormant and vegetated at this time (Rosi et al. 2018), may often generate landslide dams (Crozier 2010). They were originally triggered under different climatic and environmental settings but can be reactivated by natural causes (like rainfall or earthquake). Hence, all dormant landslides should be subject to investigation if are able to reach a stream in their pathway along the slope.

Morphometrical parameters of the landslide and the river can be used to compose geomorphological indexes, according to some authors (Swanson et al. 1986; Ermini and Casagli 2003), to assess the landslide dams formation and behaviour.

The Morphological Obstruction Index (MOI) (Tacconi Stefanelli et al. 2016) is a recent index that proved a reliable capability to assess the formation and the stability of landslide dams. Farther, the required morphometrical parameters for the index are easily obtained from common Digital Elevation Model. The MOI formula, empirically achieved from 300 cases throughout Italy, associates two important

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parameters, the landslide volume $V_1$ ($m^3$) and the valley width $W_v$ (m):

$$MOI = \log(V_l/W_v) \qquad (1)$$

The index classifies landslide dams within three evolutionary domains: formed, not formed and of uncertain evolution (no assessment can be made on its evolution). The confines of these domains are marked by two lines, the "Non-formation Straight line" and the "Formation Straight line" (Fig. 1).

The "Non-formation Straight line" is expressed as follows:

$$V_l' = 1.7 \cdot W_v^{2.5} \qquad (2)$$

With $V_1'$, called "Non-formation volume", as the minimum landslide volume ($m^3$) potentially able to block a river valley with a width of Wv. A lower volume will not realize a complete dam.

The "Formation Straight line" is expressed as follows:

$$V_l'' = 180.3 \cdot W_v^2 \qquad (3)$$

where $V_1''$, called the "Formation volume", is the smallest landslide volume ($m^3$) able to block the river valley (with 99% of confidence interval). It is the higher bound for not formed dams and the lower of the Formation domain.

In this work we present a simple GIS-based mapping methodology to verify the damming susceptibility at basin scale from inventoried landslides with geomorphological indexes. The method will be applied to the Arno River basin (Italy), where all the data needed for its application are available.

## Study Area and Materials

The Arno River basin is in the south-eastern portion of the Northern Apennines chain in Tuscany (Central Italy) and has a surface of 9116 $km^2$. Here hilly and mountainous areas prevail with 78% of the total surface (Fig. 2). The essential data for the application of the method, are:

- An updated landslide inventory;
- A Digital Elevation Model (DEM);
- The river network.

The landslides database of the Tuscany region was recently updated using the persistent scatter interferometry (PSI) (Rosi et al. 2018). This database is the collection of occurrences over a large temporal scale and is an "historical inventory". About 27,500 landslides in the new inventory belong to the Arno River basin. The landslides surface ranges from $1 \times 10^2$ to $5 \times 10^6$ $m^2$ and most of them (about 98%) can be classified as rotational or planar slow-moving slides.

A DEM with resolution of 10 m and a vector layer of the river network are also needed.

## Method

The width of each river valley can be seen as a static parameter in the MOI equation, since it does not significantly change over the time. Starting from this simplification, according to Eqs. (2) and (3), if the average river with $W_v$ within each river stretch is evaluated two threshold values $V_1'$ and $V_1''$ (Non-formation volume and Formation volume) can be computed. $V_1'$ is the smallest volume of formation, below which a landslide is not able to realize a complete obstruction, and $V_1''$ is the smallest value above which an obstruction is definitely realized.

Through some assumptions and simplifications with a landslide inventory, we can estimate the landslide volumes. Landslides with volume bigger than $V_1'$ and $V_1''$ for their river section are identified as potentially susceptible to dam the river. From these assumptions a "Map of the Damming Susceptibility" for reactivation of mapped landslides can be produced employing a GIS software.

As preliminary operations it is suggested to remove unnecessary data. The river obstruction happens exclusively in hilly or mountainous areas, specially along steep slopes
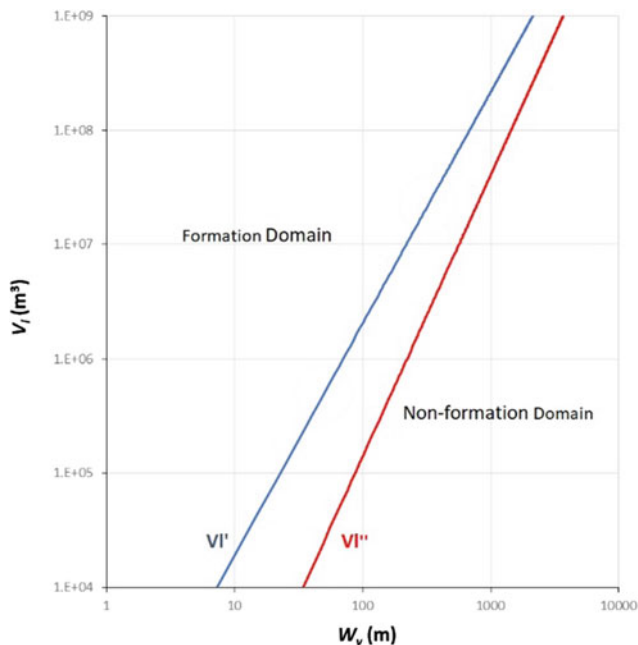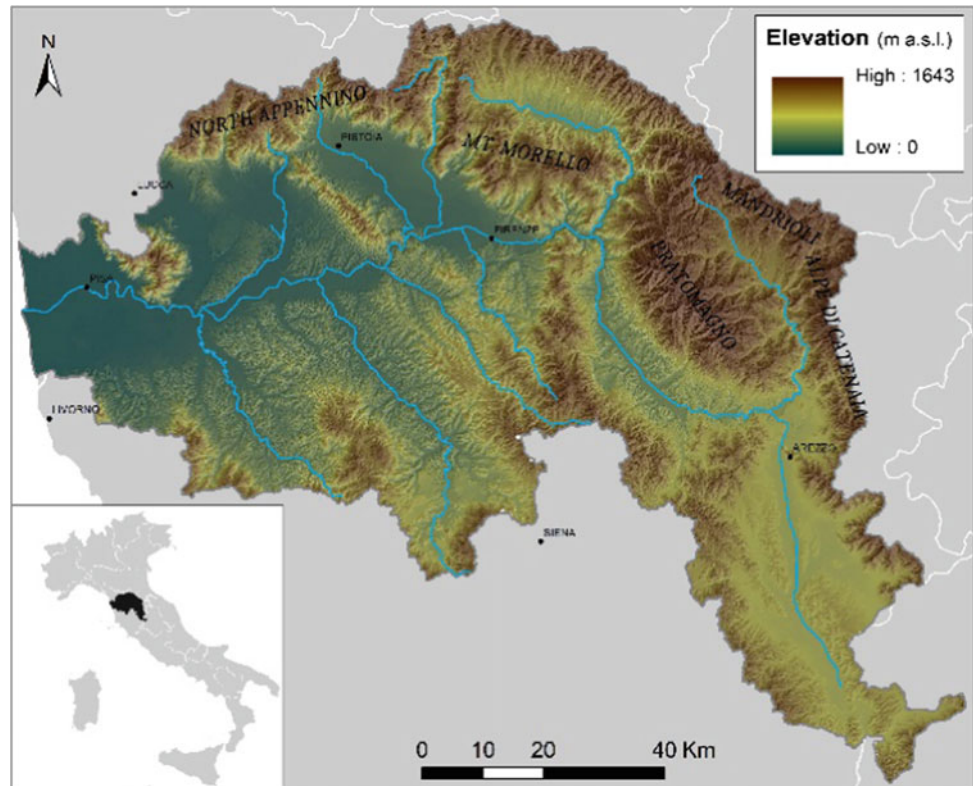


**Fig. 1** Plot of the non-formation line and formation line

(Costa and Schuster 1988; Tacconi Stefanelli et al. 2015, 2018). For this reason, flat areas (slopes below 5° and elevations below 150 m a.s.l.) have been discarded from the elaborations. Short river stretches have small upstream drainage basins and the consequences of a landslide dam here would be insignificant. For these reasons, river stretches with length shorter than (arbitrary) 20 m were not considered. Furthermore, to make maps clearer, the river network has been divided in river stretches 300 m long.

With the spreading of remote sensing data and GIS applications tools that allow the extraction af landform information at basin scales are now widely used in natural science studies. Wood (1996, 2009) have realized "LandSerf" software (integrated in SAGA GIS software), able to classify landforms from DEMs, deriving land-surface parameters (curvature, slope and aspect) used in a multi-scale approach for pattern recognition and texture analysis. With this tool is possible to classify the landscape into homogeneous morphometric units (e.g. ridges, pits, channels and planes) and isolate the channels morphological units in the form of polygons, which can be used to define the valley floor limits. To associate a valley width value, $W_v$, to each river stretch, the distance between the two valley floor boundaries have to be measured. Lines 500 m long outdistanced by 20 m and perpendicular to the river network (hereafter "transects") are created. Then, the valley floor boundaries polygons are used to "cut" the

perpendicular transects 500 m long. The median value between the transects length intersecting each river stretch is used as valley width value, $W_v$. At this step, the two landslide values of "Non-formation volume" and "Formation volume", $V_l'$ and $V_l''$, can be easily calculated applying Eqs. (2) and (3).

It is realistic that a reactivated landslide will move downstream. Draining directions within each slope can be easily computed with a GIS software. Each landslide can then be related to the river stretch that it should reach trough the draining surfaces.

To assess the landslide volumes, according on the type of movement, two procedures have been followed, one for rotational slides and one for the remaining type of movements.

Volumes for rotational slides are computed, assuming a semi ellipsoidal sliding surface, employing the equation in WP/WLI (1990), as follows:

$$V_l = \frac{1}{6} \cdot \pi \cdot D_r \cdot L_r \cdot W_r \qquad (4)$$

where $D_r$ is the sliding surface depth (m), $L_r$ the distance between the toe and the crown of the landslide (m) and $W_r$ the perpendicular distance to $L_r$ between the lateral bounds of the landslide (m). All the other landslide movement types different from rotational slides, a simplification is taken assuming a planar sliding surface with a constant depth

**Table 1** Comparison between landslide volumes, $V_l$, with the volume of non-formation, $V_1'$, and formation, $V_1''$

|  | $V_1 > V_1'$ $(V_1'')$ | $V_1 < V_1'$ $(V_1'')$ $< V_1 \cdot 1, 2$ | $V_1 < V_1'$ $(V_1'')$ |
|---|---|---|---|
| P value | 2 | 1 | 0 |

(Cruden and Varnes 1996). The landslides volume is computed with the following equation:

$$V_l = A \cdot D_r \tag{5}$$

with A (m$^2$) is the landslide surfaces, automatically calculated in a GIS software. In Eq. (5) constant landslide depth of 1.0 m was assumed according to the average soil thickness in the region as reported by Catani et al. (2010) and Bicocchi et al. (2019). This simplification can only be valid for specific areas and it is possible only in well-studied areas. These procedures for landslide volume calculation are based on some simplifications, since they use geometric approximations, but still give the magnitude of the process and can be useful for the study purposes.

The classification of the damming predisposition for each landslide start following Table 1: comparing the boundary volume of Non-formation or Formation ($V_1'$ or $V_1''$) with the landslide volume, $V_1$, a P value (Predisposition value) of 2 is assigned if $V_1$ is bigger than $V_1'$ (or $V_1''$), and a value of 0 (zero) if it is smaller. If the $V_1'$ (or $V_1''$) value is higher than $V_1$ but lower than the $V_1$ improved by 20% ($V_1 \cdot 1, 2$), a value of 1 is assigned. The $V_1$ increase of 20% (an arbitrary value) is used to avoid any underestimation during parameter sampling for a cautionary principle.

Combining the two P value obtained from Table 1 for volume of Non-formation or Formation is possible to attribute to each mapped landslide the damming predisposition through the intensity matrix of Fig. 3.

The damming predisposition is divided in five (qualitative) classes: Very Low (dark green), Low (light green), Moderate (yellow), High (orange) and Very High (red). The gray boxes are not possible combinations.

## Results and Discussions

The assessment of damming predisposition on landslide inventory of the Arno River basin is shown in Fig. 4, where most exposed areas to damming are the Mt. Morello-Pratomagno and the Mandrioli-Alpe di Catenaia mountain ridges. The class distribution between mapped landslides is shown in the histogram of Fig. 5. The Very



**Fig. 3** Matrix used to assign the damming predisposition intensity to the mapped landslides (from Tacconi Stefanelli et al. 2020)

Low class is the most frequent, with 94.40% of the whole inventory, followed by the 4.34% of the Moderate. The remaining 1.26% is divided among Low (0.78%), Very High (0.46%) and High (0.02%) classes. The mapping method result was then compared for validation with known landslide dams in the area (from Tacconi Stefanelli et al. 2015). All censed landslide dams in Fig. 4, except by one in the southwestern part of the basin, are in area with higher concentration of landslides classified with High and Very-High damming predisposition.

This agreement between the mapping result and the censed landslide dams can be considered as a positive demonstration of the reliability of the method despite several simplifications and approximations.

## Conclusions

A tool able to identify the areas with higher damming risk could radically reduce the reconstruction costs, allowing to focus monitoring works, planning activities and preventive measures.

The goal of this work was to propose a useful and easy tool to predict which areas have a higher damming susceptibility to reactivation of existing landslides. The proposed methodology was developed using the Morphological Obstruction Index and few common data and applied with some simplifications and approximations on a test area, the Arno River basin. The result is a practical and realistic map of the predisposition of the censed landslides to block the river course which agree with known past damming episodes.
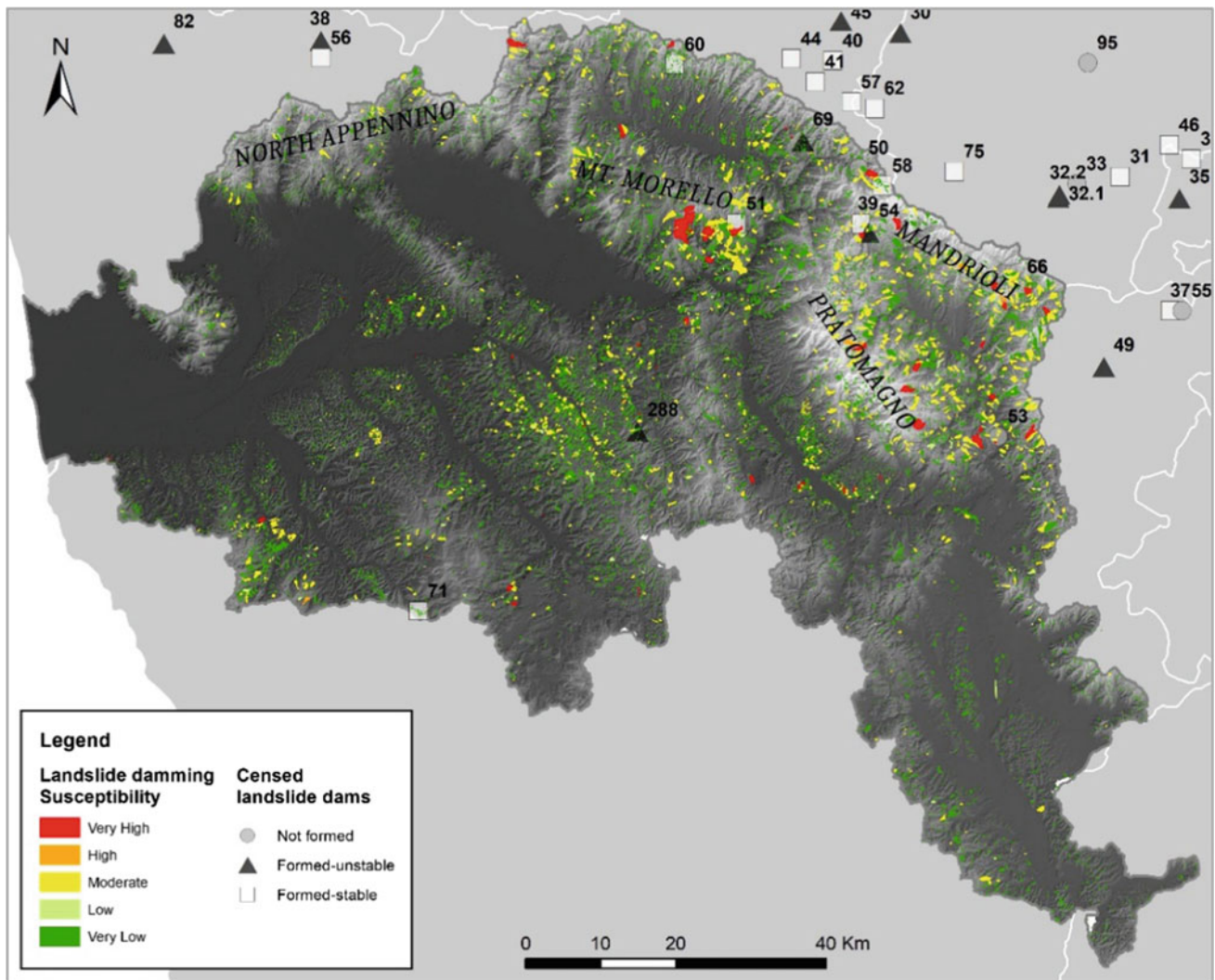
**Fig. 4** Map of Damming Predisposition in the Arno River basin by reactivation of mapped landslides and censed landslide dams (from Tacconi Stefanelli et al. 2015, bold numbers are the dam IDs, with Not-formed: only a partial damming of the stream is realized;

Formed-unstable: the natural dam and the lake are formed but has collapsed; Formed-stable: the dam is formed and the lake still exists or has disappeared for sediment filling)
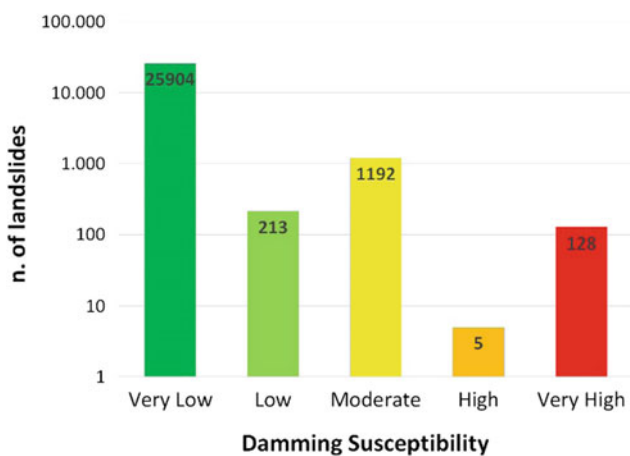


**Fig. 5** Damming predisposition of mapped landslides in the Arno River basin

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