Assessing Landslide Dams Evolution: A Methodology Review

Carlo Tacconi Stefanelli, Samuele Segoni, Nicola Casagli, and Filippo Catani

Abstract

In hilly and mountainous regions, landslide dams can be recurring events involving river networks. A landslide dam can form when sliding material reaches the valley floor and closes a riverbed causing the formation of a water basin. Unstable landslide dams may collapse with catastrophic consequences in populated regions because of the resulting destructive flooding wave released. To prevent these consequences, the assessment of landslide dam evolution is a fundamental but not easy task, because of the complex interaction between watercourse and slope dynamics. Several researchers proposed geomorphological indexes to evaluate dam formation and stability for risk assessment purpose. These indexes are usually composed by two or more morphological parameters, characterizing the landslide (e.g. sliding material volume or velocity) and the river (e.g. catchment area or valley width). In this work, a procedure to evaluate landslide dam evolution is applied and reviewed. About 300 obstruction cases occurred in Italy were analyzed with two recently proposed indexes, the Morphological Obstruction Index (MOI) and the Hydromorphological Dam Stability Index (HDSI). The former, which combines the landslide volume and the river width, is used to identify the conditions that lead to the formation of a landslide dam or not. The latter, which combines the landslide volume and a simplified formulation of the stream power (composed by the upstream catchment area and the local slope), allows a near real time evaluation of the stability of a dam after its formation. The two indexes show a good forecasting effectiveness (61% for MOI and 34% for HDSI) and employ easily and quickly available input parameters that can be assessed on a distributed way even over large areas. The indexes can be combined in a convenient procedure to assess, through two subsequent steps, the final stage in which a landslide dam will evolve.

Keywords

Landslide dam • Geomorphological index • Landslide dam stability • Flooding hazard • Landslide • Rivers

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Introduction

Landslide dams formation and failure are rather common events in hilly and mountainous regions around the world, causing hazards such as backwater ponding, outburst floods and debris flows on exposed people and properties. Through correct urban planning and flood risk management (Van Herk et al. 2011) the potential damages and correlated significant consequences can be limited. This has stimulated many efforts to assess dams formation and failure using quantitative methods with prevention purpose. Morphological indexes, composed by parameters describing involved elements (the valley, the river, the landslide, the dam and the lake), have been commonly employed to perform such analysis (Swanson et al. 1986; Ermini and Casagli 2003; Dong et al. 2011; Dal Sasso et al. 2014). Regardless their application at local scale, the use of parameters (e.g. discharge, granulometry) that can be accurately estimated only by local survey is troublesome and their assessment over a broad area is difficult (Dong et al. 2011; Dal Sasso et al. 2014). If a large number of landslide dams have to be characterized for prevention or planning activities the employ of parameters that can be easily defined on a distributed way (e.g. morphometrical data via DTM analysis with GIS software) is preferable.

In this paper, a practical methodology to assess landslide dam formation and evolution is presented. This simple method, suitable for large areas and based on the combination of two geomorphological indexes with good prediction effectiveness, is applied to the wider Italian landslide dam database.

Materials

Landslide dams are rather frequent in Italy because its geological and geomorphological characteristics. Tacconi Stefanelli et al. (2015) realized a homogeneous database with a morphometrical characterization of 300 landslide dams collected in Italy (Fig. 1). The inventory, realized mainly by photointerpretation and revision of historical and bibliographical data, characterize each case with a series of information and morphometric attributes taking into account six different aspects: the Localization, the Consequences, the Landslide, the Dam, the Stream and the Lake.

According to their evolution to present, landslide dams are classified in the database in three classes:

– Not Formed: the landslide reduces the riverbed section without forming an upstream basin. The partial damming can evolve with the river path diverted or the landslide toe eroded. It does not cause significant damage.

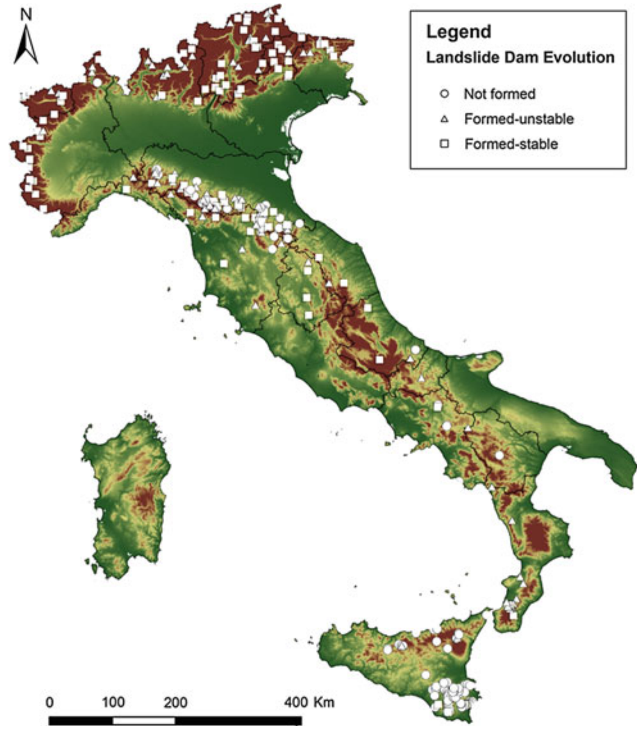

Fig. 1 Landslide dams distribution of Italian, according to three evolution classes (modified from Tacconi Stefanelli et al. 2015)

– Formed-Unstable: the river is completely obstructed by the landslide and upstream, a lake basin is formed. The dam collapses after a variable time (from hours to centuries) and releases a destructive flooding wave threatening life and property, making it the most dangerous case. Dams artificially stabilized or removed for prevention reasons are included in this class as well.
– Formed-Stable: complete obstruction of the river and formation of a dam and an upstream lake, which can be still present or filled by sediments. The dam may be overtopped by water in the past, but it did not suffered total failure producing catastrophic flooding wave.

The frequencies of the three groups are almost equally distributed, as the most frequent class is the formed-stable dams with 39% followed by the not formed dams with 33%, then by the formed-unstable with 28%.

Methodology

The possible evolution process of a dam may be described by the three evolution classes noted above, proposed by Tacconi Stefanelli et al. (2016) in a two consecutive steps flow chart (Fig. 2). At the start of the first step, a landslide involves a riverbed. If the landslide does not realize a

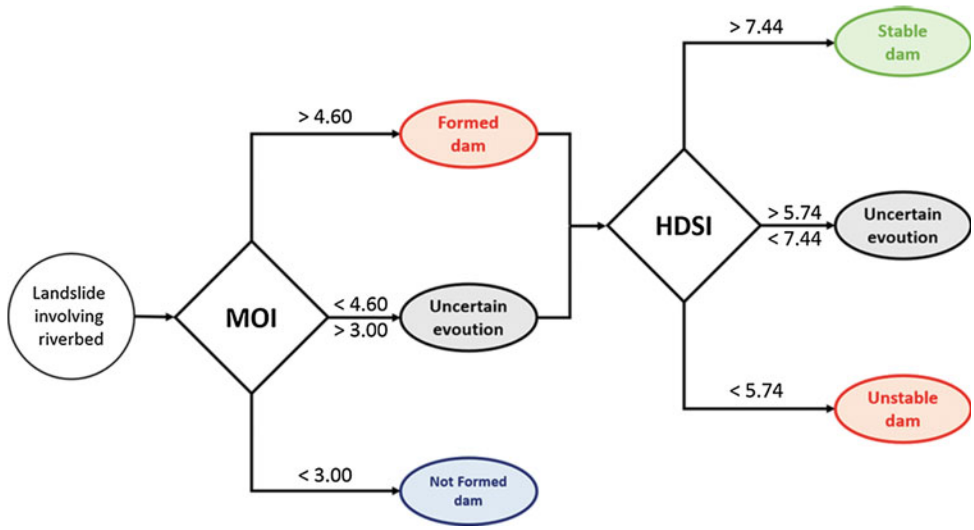

Fig. 2 Flow diagram of the operational procedure for landslide dam formation and stability evaluation (modified from Tacconi Stefanelli et al. 2016)

complete obstruction, the case is classified as "not formed". In the other case, or if the formation is unsure, the flow moves to the second step, where the stability of the formed dam is evaluated. It is classified as "formed unstable", if it can potentially collapse (after an undefined period), or as "formed stable", if it is not going to collapse. The path in the flow process is guided by the assessment of two geomorphological indexes (Fig. 2), first the "Morphological Obstruction Index", MOI:

$$MOI = \log\left(\frac{V_l}{W_v}\right) \quad (1)$$

and than the "Hydromorphological Dam Stability Index", HDSI:

$$HDSI = \log\left(\frac{V_l}{A_b \cdot S}\right) \quad (2)$$

where V_l is the landslide volume (m^3), W_v the dammed valley width (m), Ab the upstream catchment area (km^2) and S the local longitudinal slope of the river. The MOI relates the valley width W_v with the landslide volume V_l able to realize a complete obstruction; the HDSI compare the landslide volume V_l and the erosive capacity of the river, represented by the simplified geomorphological formulation of the stream power $A_b \cdot S$, to predict the landslide stability.

Results

The results of the two indexes applied to the Italian landslide dams are shown in Fig. 3 and Table 1. Data belonging to the same evolution classes are grouped on the graphic into evolution domains. The limits a domain is defined according to the extreme values of the evolution class inside it.

For the MOI index the domains are (Fig. 3a): the Non-formation domain (MOI < 3.00), including only landslide not blocking a riverbed, contains 15% of the total; the Uncertain Evolution domain (3.00 < MOI < 4.60), with both formed and not formed dams, contains about 39% of the dataset; the Formation domain (MOI > 4.60), with only landslides that blocked the valley, contains 46% of the dams (see Table 1). Two dashed lines, the lower Non-formation Line and the upper Formation Line, bound the Uncertain Evolution domain that contains the lowest formed and the highest not formed dam.

The HDSI index identify three domains as well in Fig. 3b: the Instability domain (HDSI < 5.74), with only not formed dams; the Uncertain Determination domain (5.74 < HDSI < 7.44), containing both stable and unstable dams; the Stability domain (HDSI > 7.44), with stable dams. The Uncertain Determination domain is encompassed by two dashed lines as well, the upper Stability line and the lower Instability line, comprehend the highest instable and

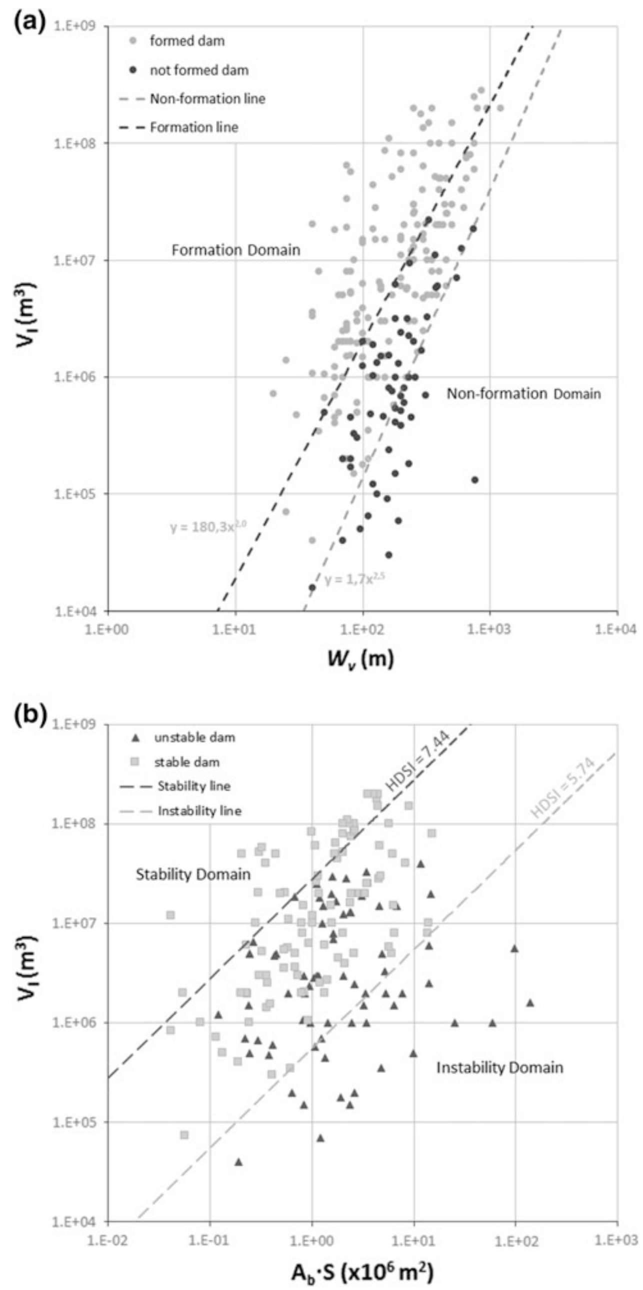

Fig. 3 Bi-logarithmic diagrams of: **a** Morphological Obstruction Index and **b** Hydromorphological Dam Stability Index

the lowest stable dam respectively. This domain is quite extended, with 66% of the total formed dams, while the Stability domain contains 19% of the formed cases, and the Instability domain includes 15% of them (see Table 1).

Table 1 Landslide dams distribution inside MOI and HDSI domains

HDSI domains	Formed dams (n.)	Not formed dams (n.)	% of total
Non-formation	0	34	14.6
Uncertain Evolution	58	33	39.0
Formation	108	0	46.4
MOI domains	Formed dams (n.)	Not formed dams (n.)	% of total
Non-formation	0	34	14.6
Uncertain evolution	58	33	39.0
Formation	108	0	46.4

Conclusion

In this work, a contribution in the rapid damming hazard assessment using practical geomorphological tools has been presented. Two morphological indexes, i.e. Morphological Obstruction Index (MOI) and Hydromorphological Dam Stability Index (HDSI), realized to improve previous methods characteristics (Tacconi Stefanelli et al. 2016) as the easy availability of the input data and the prediction effectiveness, were examined. The MOI allows a reliable analysis and a morphological assessment of landslide ability to block a river, as 61% of the dams in the dataset were correctly classified as formed or not formed. As displayed by the Italian cases, assuming the same valley width, the larger the volume of the landslide, the greater the damming probability. The HDSI correlates landslide volume and a morphological proxy for discharge in order to evaluate the long-term stability of a landslide dam. Even with a wide area of uncertain evolution, 34% of the cases fall in their own class and as the index value increases the general stability of the dam also increases. The high geological and climatic variability in the Italian territory may be responsible for the wide uncertain domain.

A fast operational procedure employing these indexes is presented as a useful tool to carry out a preliminary estimation of landslide dams evolution. This procedure can be employed at basin or smaller scale for forecasting and planning purposes. In the first step, MOI can be used to classify formed and not formed dams. Then, if a case results in a landslide dam, HDSI can be used to discriminate between stable or unstable dams.

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