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Geomorphic indexing of landslide dams evolution

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ABSTRACT

Landslide dams are rather common events in hilly and mountainous areas and they occur when a landslide reaches a valley floor closing the riverbed. If they form a lake basin, unstable landslide dams can have catastrophic consequences when they occur in upstream of populated regions. Landslide dam behavior is not completely understood yet, however several studies suggested implementing geomorphological index in order to assess their formation and evolution. These indexes result from the composition of two or more morphological attributes that characterize the landslide (e.g. landslide volume or length) and the involved river valley (e.g. valley width).

The objective of this work is the definition of a procedure, based on the joint use of different indexes, to assess landslide dams evolution over large areas (e.g. entire river catchment or even a region or a nation) and in short times, in order to be used for emergency response or for planning activities.

About 300 landslide dam events collected in Italy were analyzed and some state-of-the-art geomorphological indexes were applied to characterize the damming phenomena at the national scale. To overcome some limitations of the aforementioned indexes, we introduce two new indexes: the Morphological Obstruction Index and the Hydromorphological Dam Stability Index. The former combines the river width and the landslide volume, and it can be used to identify the conditions associated to dam formation discriminating between circumstances where a landslide dam is formed and circumstances where it is not. The latter uses a simplified stream power formulation (combining the upstream catchment area and the local slope gradient) to account for the river energy. This index allows evaluating the stability of a dam in near real time as soon as it occurs and can be used to discriminate between stable and unstable dams.

If compared with the reviewed state of the art indexes, the newly proposed ones show an improvement in the forecasting effectiveness and have the advantage of being based on morphometric input parameters that can be easily and quickly assessed on a distributed way even over large areas. We propose a tool that is based on the joint use of the newly proposed indexes and that can be used to provide fast and effective assessment on landslide dam formation and stability during emergency or planning activities.

1. Introduction

Landslides involving river channels can alter the hydrological dynamics, up to the extreme consequence of the stream blockage (Costa and Schuster, 1988; Canuti et al., 1998; Ermini and Casagli, 2003; Korup et al., 2006). If the sliding materials are not able to completely block the riverbed, the impact on the fluvial network is usually limited. Conversely, when the obstruction is complete, it may originate dammed lakes and upstream areas may be flooded over kilometers, as the 60 km long lake formed by the Usoi landslide dam, Tajikistan, in 1911 (Schuster and Alford, 2004). If the dam is stable, the basin can last even for centuries until sediments fill it, otherwise the dam can collapse causing serious hazard to life and property. In downstream areas, a dam breach may lead to destructive events, such as anomalous flood waves, which can generate lasting effects on the natural environment and infrastructures. One of the worst historical flooding events is the breaching of the seismic induced dam on the Daru River, China, in 1786, with over 100,000 fatalities (Dai et al., 2005).

Since in many countries the human settlements and activities are mainly established in valley floors, the consequences can be tragic, causing significant economic damages and casualties (Pirocchi, 1992; Casagli and Ermini, 1999). These situations can be limited through accurate urban planning and flood risk management (Van Herk et al., 2011; Plate, 2002). However, in the international literature it has never been established a tool for the fast and effective assessment of the river obstruction and of the dam stability, to be used over large areas for emergency response or to forecast hazard scenarios.

In Italy, characterized by a wide geological, morphological and climatic variability, landslide dams and related flooding are rather

Abbreviations: DataBase, Italian Landslide Dams Database (Tacconi Stefanelli et al., 2015); BI, Blockage Index; ACR, Annual Constriction Ratio; DBI, Dimensionless Blockage Index; MOI, Morphological Obstruction Index; HDSI, Hydromorphological Dam Stability Index.

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frequent (Guzzetti and Tonelli, 2004; Salvati et al., 2010). Nevertheless, the scientific study about this topic has started only after the impressive episode of Val Pola (Sondrio, Northern Italy) event in 1987, when a huge landslide of 40 Mm^3 completely blocked the valley floor and the consequent evolution resulted in 29 casualties (Govi et al., 2002; Crosta et al., 2004). After this event, some authors compiled landslide dams inventories covering different portions of the Italian territory (Pirocchi, 1992; Casagli and Ermini, 1999; Coico et al., 2013) at different scales and with different standards of detail. Tacconi Stefanelli et al. (2015) homogenized these inventories and new data to set a national-scale archive of 300 landslide dams occurred in Italy, with their main morphometric parameters. Other examples of national scale inventories of landslide dams are those built in New Zealand (Korup, 2004), China (Peng and Zhang, 2012) or Switzerland (Bonnard, 2011).

Existing landslide dam databases are a fundamental resource, since the analysis of past events represents a fundamental step to identify which parameters played a role in their formation and evolution. A common methodology used in quantitative geomorphological analysis is to employ morphometric relationships (Strahler, 1957; Troiani and Della Seta, 2008; Font et al., 2010; Larsen et al., 2010). According to some studies, geomorphological indexes can be used to assess landsldie dam formation and evolution (Swanson et al., 1986; Ermini and Casagli, 2003; Korup, 2004; Cui et al., 2009; Dong et al., 2011; Fan et al., 2012; Peng and Zhang, 2012; Dal Sasso et al., 2014). Geomorphological indexes are composed by variables characterizing the different involved elements (the landslide, the dam, the valley, the river and the lake) and aim at simulating their interactions in a complex geomorphological system. Moreover, concerning practical applications, indexes with high significance can be used to forecast and discriminate between possible dam evolutions. Many geomorphological indexes are used in studies focusing on a single landslide dam (Hermanns et al., 2004; Nash et al., 2008; Duman, 2009). Although some of these indexes can be conveniently used in local scale applications, their use over broad areas (e.g. in national scale studies) is problematic. This is especially true for those indexes that are based on parameters (e.g. peak flow, dam's material granulometry) that can be assessed with sufficient accuracy only by punctual measurement, and their definition for many occurrences over a broad area is troublesome (Ermini et al., 2006; Dong et al., 2011; Dal Sasso et al., 2014). Neither they can be easily defined on a distributed way over an entire area in order to make prevention nor to assist planning activities.

When the object of the study is the characterization of the many landslides involved in a large dataset, the employ of parameters derived from distributed data (e.g. the drainage area from a DTM) and the selection of simple relationships is preferable (Costa and Schuster, 1988; Ermini and Casagli, 2003; Korup, 2004). Regarding this issue, Swanson et al. (1986) proposed two indexes through the analysis of several phenomena occurred in Japan: the Blockage Index and the Annual Constriction Ratio, both able to evaluate the landslide dam formation. Analyzing landslide dams in North Apennine, Italy, Ermini and Casagli (2002) proposed a refined version of the Blockage Index with a dimensionless formulation. Their Dimensionless Blockage Index was used to assess effectively the dam stability and evolution.

The final objective of this paper is the definition of a tool, based on the joint use of geomorphological indexes, to understand the potential evolution of landslide damming phenomena and to be used over large areas for emergency response or to assist planning activities. First, we explore the applicability at national scale of some state-of-the-art indexes on the Italian national database built by Tacconi Stefanelli et al. (2015). Then, we propose and apply to the same database two new geomorphological indexes. On one hand, the new indexes have improved forecasting effectiveness. On the other hand, these indexes are based on morphometric parameters that meet the basic principles of easy and fast data collection. Finally, we propose a combination of both indexes in order to define a tool that could be effectively used to forecast hazard scenarios for planning activities or for emergency response, in applications ranging from the local to the national scale.

2. Materials and methods

2.1. The dataset

Italy is a country endowed with a wide climatic, geological and morphological variability, manifested in high precipitations (Alps and Northern Apennine), tectonic uplift (Alps), and volcanic activity (Southern Apennine). Alps are glaciated areas with very high energy of relief and slope gradients, with elevation of up to 4000 m a.s.l. Apennines are characterized by highly variable morphology and sensible precipitation differences from north to south. A general seismic activity is present in all the Italian territory.

In this work we analyze past landslide dam events recorded in Italy, using the single most complete inventory of Italian landslide dams provided by Tacconi Stefanelli et al. (2015) (hereafter DataBase) as input data. The inventory was derived from heterogeneous sources, extensively revised, homogenized, updated and completed. It was realized through aerial photointerpretation, cartographic analysis or historical and bibliographical research and consists of 300 comparable events in all Italy. The DataBase characterizes each case with a series of morphometric parameters, including the length and volume of the landslides and the dams, the river valley width, the riverbed slope and the basin catchment area. All of them were measured through cartographic and aerial image interpretation, or estimated through historical and bibliographical data research.

In the DataBase landslide dams are subdivided in three classes, which represent the three possible final stages of their long-term evolution:

- Not-formed: the landslide reached the riverbed but, although the river flow could have been altered, the riverbed section is only reduced realizing a partial damming of the stream. The upstream lake basin did not formed and the further evolution can be a river deviation or landslide toe erosion.
- Formed-unstable: the landslide completely blocked the river, forming a natural dam and an upstream lake. However, over times that can range from hours to centuries, the dam collapsed or was breached by the river. A high level of hazard is usually associated to this class, because collapses and breaches can be associated to sudden flooding waves. A dam was classified as formed-unstable also if it was artificially stabilized or removed, because it is supposed that such interventions take place only after that a careful evaluation points out the potential instability of the landslide dam.
- Formed-stable: the blockage was complete with the formation of a dam and a lake, which are still existing or disappeared for sediment filling. The dam could have been overtopped during its life, but no total failure or destructive flooding wave occurred.

These three classes represent all the possible evolutions of a process that evolves through two distinct steps. The first step is the dam formation: either the landslide does not form a dam or the landslide forms a dam. In the first case, we have the “not formed” class. In the second case, we move to the second step, where the formed dams are discriminated between those that collapse after a given period (“formed unstable” class) and those that are potentially everlasting (“formed stable” class).

The most frequent dams described in the DataBase are the formed-stable dams with 39%, the not formed dams are 33% and the formed-unstable 28%. This distribution does not reflect the real distribution of landslide dams in Italy: historical data and landscape analysis underestimate landslides with not-formed dams and small formed-unstable events without any social or environmental consequence, since they