Landslides (2018) 15:507–521
DOI 10.1007/s10346-017-0888-6
Received: 14 February 2017
Accepted: 28 August 2017

corrected publication November/2017.

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Morphological analysis and features of the landslide dams in the Cordillera Blanca, Peru

Abstract Global warming in high mountain areas has led to visible environmental changes as glacial retreat, formation and evolution of moraine dammed lakes, slope instability, and major mass movements. Landslide dams and moraine dams are rather common in the Cordillera Blanca Mountains Range, Peru, and have caused large damages and fatalities over time. The environmental changes are influencing the rivers' and dams' equilibrium, and the potential induced consequences, like catastrophic debris flows or outburst floods resulting from dam failures, can be major hazards in the region. The studies of past landslide dam cases are essential in forecasting induced risks, and specific works on this topic were not developed in the study region. Reflecting this research gap, a database of 51 cases and an evolution study of landslide dams in the Cordillera Blanca Mountains is presented. The main morphometric parameters and information of the landslide, the dam body, the valley, and the lake, if any, have been determined through direct and indirect survey techniques. Low variability in some of the main morphometric parameter distributions (valley width and landslide volume) has been shown, most likely due to an environmental control connected to the regional tectonic and glacial history. In order to analyze present and future landslide dam evolution, a morphological analysis was carried out using two recently developed geomorphological indexes employed on the Italian territory. The results of the Cordillera Blanca analysis have been compared with a large Italian landslide dam inventory, highlighting as much the differences as the similarities between the two datasets. The long-term geomorphological evolution changes are evaluated. Many of the stable dams are in disequilibrium with their surrounding environment and their classification result is of "uncertain determination."

Keywords Landslide dams · Natural hazards · Database · Morphometric parameters · Cordillera Blanca · Peru

Introduction

Impounded lakes produced by landslides and moraines in mountain regions all over the world induce geomorphic hazards and a threat to the communities settled downstream. A sudden dam failure can release a destructive outburst flood, spreading for possibly tens of kilometers downstream (e.g., Casagli and Ermini 1999; Costa and Schuster 1988; Hewitt et al. 2008). In the literature, many single landslide dam study cases have been reported (e.g., King et al. 1989; Hermanns et al. 2004; Dai et al. 2005; Nash et al. 2008; Duman 2009; Degraff et al. 2010; Delaney and Evans 2015, 2017; Emmer and Kalvoda 2017). Several landslide dam inventories have been collected in different parts of the world, such as in North America (O'Connor and Costa 1993), South America (Hermanns et al. 2011), Europe (Casagli and Ermini 1999; Bonnard 2011; Tacconi Stefanelli et al. 2015), Central Asia (Popov 1990; Hewitt 1998; Strom 2010; Korup et al. 2010; Schneider et al. 2013), China (Dong et al. 2009; Fan et al. 2012; Peng and Zhang 2012), and New Zealand (Korup 2004). Although some reports on single events in the Cordillera Blanca Mountain Range, Peru, have been researched (Lliboutry et al. 1977; Zapata 2002; Carey 2005; Hubbard et al. 2005), no landslide dams and related lakes archive or any extended study on these topics are available yet.

Within the glacial valleys of the Cordillera Blanca, there are many elements setting up a continuous danger for the Peruvian population. Glacial lakes of different sizes have produced Glacial Lake Outburst Floods (GLOFs) (Carey 2005; Iturrizaga 2014; Vilímek et al. 2014), and methods for their hazard assessment and mitigation have been developed (Carey et al. 2012; Emmer and Vilìmek 2014; Somos-Valenzuela et al. 2014; Emmer et al. accepted). Landslide dams, or the remnants of extinct lakes (both failed and infilled), are also rather common. Therefore, one of the aims of this paper is to create a database of landslide dams in the Cordillera Blanca through a geomorphologic investigation, including both existing, failed, and infilled landslide dams. Dams and lakes were classified and described modifying an existing data form utilized for an inventory of landslide dams in Italy (Tacconi Stefanelli et al. 2015).

Landslide dams and moraine dams of the Cordillera Blanca have different origins but are prone to the same problems (e.g., difficult predictability) and endanger the population in the same way (lake outbursts with high speed and large inundated area). In general, dammed lakes in high mountain areas pose hazards because (1) the surrounding environment is characterized by very high relief energy, which produces highly destructive floods/debris flows; (2) they are downslope from glaciers and steep unstable rock slopes, susceptible to slope movements (e.g., Haeberli et al. 2016); (3) small debris flows from the steep valley sides constantly supply new material to fall on the dam body, resulting in a precarious balance of the repeatedly "rejuvenated" dam; and (4) the vegetation is not able to stabilize their slopes due to the high elevation and the rapid rate of geomorphic change on the dam body (Costa and Schuster 1988).

While glacial lakes in the Cordillera Blanca were already a subject of scientific research, a deepened study and an assessment of landslide dam evolution are necessary to fill the lack of knowledge about this topic in the region. Tacconi Stefanelli et al. (2016) studied the features of Italian landslide dams and developed two practical tools able to evaluate, rapidly and with easily achievable data, the dam formation and its stability. These indexes proved to be effective to evaluate the dam formation and its stability in the Italian territory. A morphometric analysis on the Peruvian dataset is then performed applying these two indexes, and the result is compared with the Italian dataset to study the landslide dams feature differences and to test the indexes reliability in a very different geographic area. The Italian inventory was selected because it is significantly large, complete, and well constrained with respect to the average of the available databases.

Study area

The Cordillera Blanca (Spanish for "White Range") is part of the tectonically highly active Andes range, formed by collision of the Nazca, South American and Antarctic (partly) lithospheric plates and is also part of the continental divide. It is located in the Western Cordillera in the Northern part of Peru and includes 33 major peaks over 5500 m in elevation and an area 21 km wide and about 200 km long (Fig. 1).

The highest mountain in Peru, Nevado Huascarán (6768 m a.s.l.), is located in this range. The high elevation differences between peaks and valley bottoms reach at some places 3500 m (Iturrizaga 2014), which is important to characterize the relief energy. The Rio Santa is the main basin and its valley, which has been affected by many historical natural disasters (Lliboutry et al. 1977; Zapata 2002; Klimeš 2012; Klimeš et al. 2015), marks the northwest side of the Cordillera Blanca. Most of the western part of the Cordillera Blanca is part of the Rio Santa catchment (outlet at Pacific Ocean), while the eastern slopes are drained into the Marańon River (Atlantic Ocean). The most southern part belongs to the Pativilca River catchment (Pacific Ocean). The central part of the Cordillera Blanca is formed by a batholith of Tertiary age, which consists of coarse grained granodiorites and tonalites (Klimeš 2012).

During the last two centuries, global climate change has led to glacial retreat (Thompson et al. 2000; Vuille et al. 2008; Schauwecker et al. 2014), resulting in thinning and fracturing of glaciers, formation of moraine dammed lakes (Hubbard et al. 2005; Vilímek et al. 2005), and slope instability, often involving river channels with the obstruction of valleys. All these consequences induced a range of significant hazards on the territory,

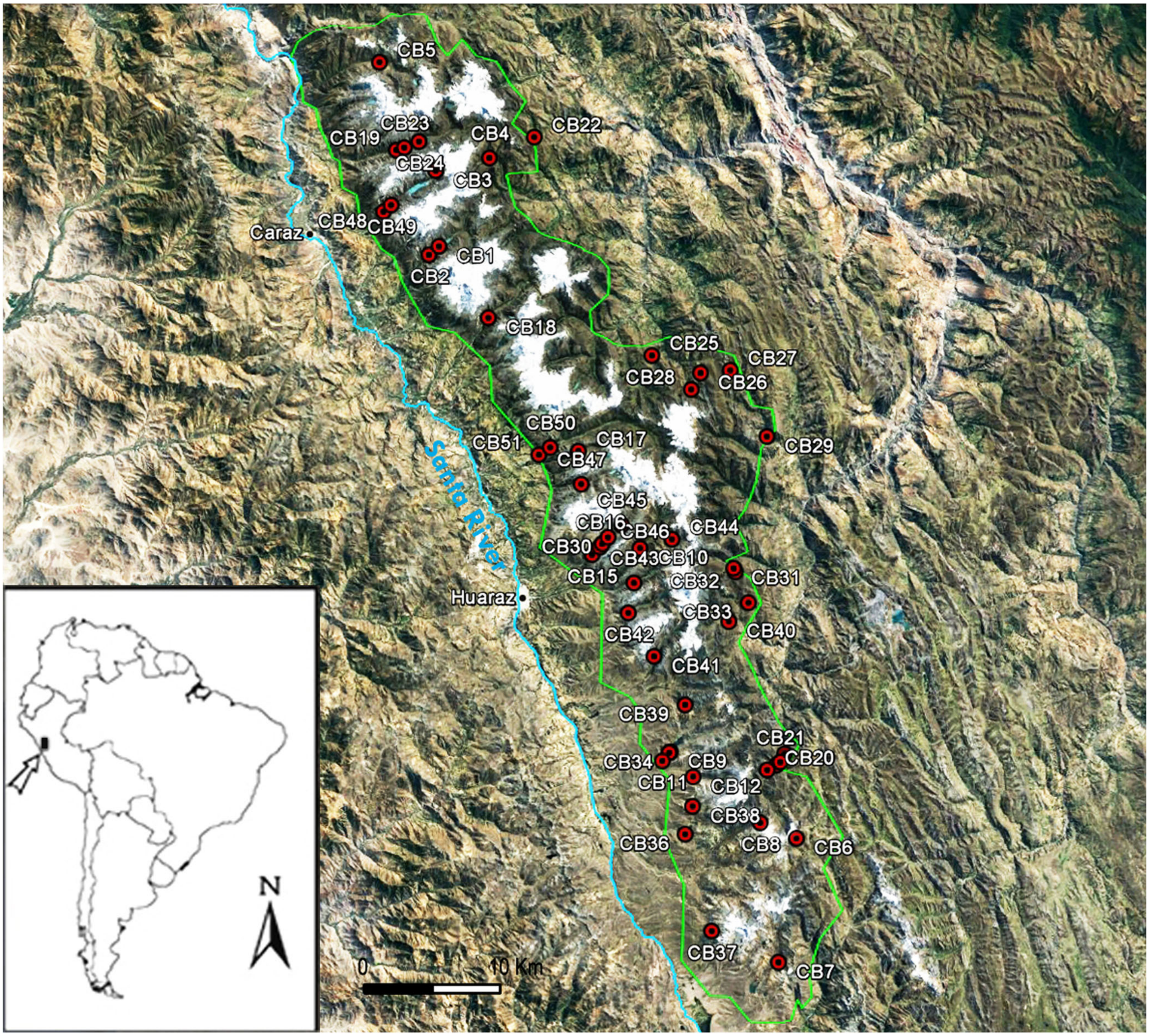

Fig. 1 Map of Cordillera Blanca mountain range (green line is the border of the National Park Huascarán) showing the collected landslide dams (red dots) and the Santa River path (blue line)

Table 1 Information fields of the database with unit of measure and short description

Information	Unit	Description
ID	[ ]	Unique identification number of the landslide [CB##]
Locality	text	Local name where damming occurred
Position	[###;###]	E and N coordinates of the landslide dam (WGS 1984-UTM)
L. Mov.	text	Landslide movement classification (Cruden and Varnes 1996)
V_l	[m^3]	Volume of the landslide
d type	[ ]	Classification of the dam (Costa and Schuster 1988)
V_d	[m^3]	Volume of the dam
Q_d	[m] a.s.l.	Elevation of the spillway (above sea level)
d Cond.	text	Dam condition (Casagli and Ermini 1999)
Evolution	text	Evolution of the landslide dam (Tacconi Stefanelli et al. 2015)
W_v	[m]	Valley width
Catch. A	[km^2]	Catchment area of the basin subtended by the landslide dam
S	[°]	Steepness of river bed
Lake Cond.	text	Lake condition (Casagli and Ermini 1999)

such as catastrophic debris flows or outburst floods resulting from dam failures (Lliboutry et al. 1977; Carey 2005; Vilímek et al. 2005; Iturrizaga 2014). The most destructive slope deformation in the Peruvian mountains was the event of May 31, 1970. An ice and rock fall, triggered by an earthquake with magnitude 7.7 (Plafker et al. 1971; Evans et al. 2009; Klimeš et al. 2009), fell from the Nevado Huascarán. The unleashed avalanche formed a wave of water, rock, and ice that traveled in SW direction more than 14 km in less than 3 min (Carey 2005), burying the city of Yungay with 18,000 fatalities and damming the Rio Santa for a short time. However, Evans et al. (2009) recently published a significantly lower estimation of 6000 fatalities.

Materials and methods

The inventory

All the information about the damming cases (the landslide, the dam, the valley, and the lake) were determined with indirect and direct survey techniques. An in-depth geomorphological investigation through maps, research, and aerial photo interpretation allowed the authors to identify the dam sites and collect the morphometric parameters. In particular, in the main part of the survey, the following data have been used: a Digital Terrain Model (DTM) covering the entire Cordillera Blanca Mountain Range with 30 m of spatial resolution (data obtained by the NASA Shuttle Radar Topography Mission, SRTM, and available from the US Geological Survey) and satellite images available for viewing on *Google Earth* and *Bing* were examined. For a part of the cases, aerial photos and topographic maps, dating back since the 1940s with spatial scales from 1:10,000 to 1:25,000, available from the Autoridad Nacional del Agua (National Water Authority) in Huaraz (Peru) were studied. In order to check the evolution of the dams, a multi-temporal image analysis was carried out, but this did not provide information on the age of the landslide dams. A topographic and morphometric field survey was undertaken only for a few cases, because of the inaccessible locations in high elevation and remote mountain areas of most locations. During the research, several dammed lakes located in landslide bodies were found. These particular cases are not included in the Peruvian inventory because they are not present in the comparison database and some of their morphometric parameters (e.g., valley width or landslide volume) are hardly achievable (too subjective).

Table 2 Geomorphological classification of landslide dam

Dam type	Description
I	No complete river obstruction; the landslide is small compared with the valley width.
II	The landslide completely crosses the valley and can realize a river obstruction.
III	Complete obstruction; the landslide has a big volume and move upstream and downstream of the valley.
IV	Complete obstruction; dam formed by two landslides from the opposite slopes of the valley.
V	Complete obstruction; damming produced by multiple lobes of the same landslide
VI	May cause a complete obstruction; landslide with sliding surface under the stream

Source: Costa and Schuster 1988

Table 3 Classification of dam condition

Dam condition	Description
Partial blockage	The obstruction of the riverbed is not complete (type I of Costa and Schuster (1988) classification). An impoundment is not realized, and the riverbed section is reduced.
Toe erosion	The lower part of the landslide is eroded by the stream.
Artificially cut/stabilized	The landslide dam is cut/stabilized through the human work.
Slightly/strongly cut	The dam body is cut with small (less than 50% of the height) and high (more than 50% of the height) intensity.
Not cut	The dam has not been cut .
Breached/partly breached	The dam completely/partly collapsed.

Source: Casagli and Ermini 1999

The data on landslide dams in the Cordillera Blanca were gathered together in a clear structure simplifying an existing database proposed by Tacconi Stefanelli et al. (2015). The authors created a complete database structure composed of 57 information fields on geomorphic parameters (e.g., on the landslide, the dam body, the valley, and the lake, if present) and general information about the event. The data are easily retrievable to support future use and update of the database and in order to guarantee a good quality of data retrieval, also by non-expert data collectors.

For the landslide dams in the Cordillera Blanca, the original database structure by Tacconi Stefanelli et al. (2015) has been modified selecting only 14 essential information fields (Table 1).

Most of the data fields about the landslide, the dam, the stream and the lake consist of morphometrical data and few multiple constrained choices (movement, dam type, dam and lake conditions). Descriptive and note fields in the data form are avoided, with the purpose of making the survey as objective as possible. Each event is identified by a unique ID number preceded by "CB" (acronym for Cordillera Blanca) and is located according to the geographical position of the dam's spillway. The landslide type of movement follows the characterization of Cruden and Varnes (1996). The dam characterization is supported by the geomorphological classification of Costa and Schuster (1988), and the dam and lake conditions are described with the classes proposed by Casagli and Ermini (1999) (see Tables 2, 3, and 4).

Table 4 Classification of dammed lake condition

Lake condition	Description
Not formed (generic)/for erosion/for infiltration/for deviation	No lake was formed; the cause can be specified (for erosion, infiltration or deviation)
Existing/existing partly filled	The lake still exist but can be partly filled by sediments
Disappeared (generic)/for man-made influence/spillway erosion/filling/dam collapse	The lake no longer exists; the cause can be specified (man-made influence, spillway erosion, filling, or dam collapse)

Source: Casagli and Ermini 1999

To compute landslide and dam volumes (Landslide body and Dam body in Fig. 2), a simple procedure has been followed. Regardless of the starting landslide movement (e.g., slump or flow), the basal surface of the displaced mass filling a generic U-shape glacial valley can be simplified assuming a semi-ellipsoidal surface. Displaced mass volume (V) can be approximated assuming a semi-ellipsoidal shape, according to Catani et al. (2016), with the following empirical equation:

$$V = 1\Big/6\ \pi DWL \tag{1}$$

where D, W, and L are the depth, the width, and the length of the displaced mass (landslide or dam), respectively (Fig. 2). When more than one landslide causes the obstruction at the same time, we take into account the total volume of the coalescent landslides. Concerning the dam volume, we considered only the part of the displaced mass that actually obstructs the river valley (Dam body in Fig. 2) without the upper part (Canuti et al. 1998). The required morphometric parameters were in majority derived by geomorphological analysis of the available topographic data using a GIS software or in the minority cases measured with a laser meter on site.

Concerning the valley width, it is not always easy to identify this attribute clearly. According to the valley profile (U- or V-shaped), in some cases (e.g., in narrow valleys), there is a clear border between the valley floor (usually flat) and the lateral slopes in the cross profile. When the valley turns gradually into the slope (Fig. 3a), we measured the width of the valley at the level of lower part of the accumulation (Q_d, the elevation of the dam's spillway in Table 1) from the lateral slopes (Fig. 2).

The severity of consequences of a landslide dam is connected with the dam evolution after its formation. For this reason, landslide dams are described using three classes based on their evolution: not formed, formed-unstable, and formed-stable (Tacconi Stefanelli et al. 2015). In the first class, the landslide reached the riverbed influencing it but did not form a proper lake, due to an incomplete obstruction. Then, the possible further evolutions for this class are the river deviation or the landslide toe erosion. In the other two classes, a complete dam is formed. The unstable dams collapse after a variable span of time (from hours to centuries) and

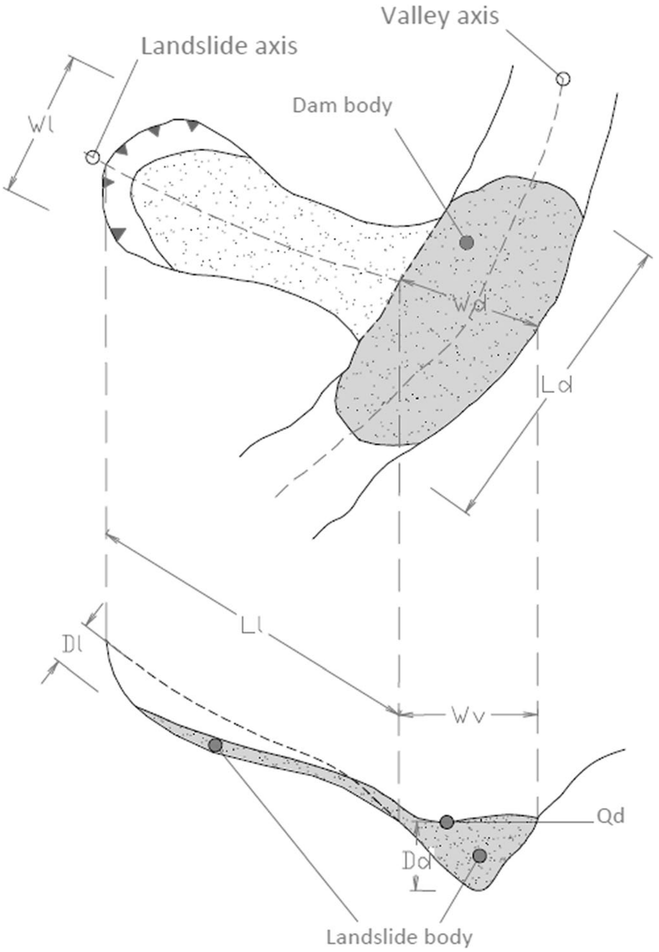

Fig. 2 Plan and cross-section view of a generic landslide dam, where L_l, W_l, and D_l are the landslide length, width and depth; L_d, W_d, and D_d are the dam length, width, and depth; W_v is the valley width; and Q_d is the elevation of the dam spillway

release a catastrophic outburst flood (Costa and Schuster 1988; Canuti et al. 1998). The stable ones never show complete collapse and are preserved until present, even if some overtopping has occurred cutting it, and/or disappeared through filling processes. Unfortunately, usually no dating information about past dam formation or failure is available. Only the failures from Nevado Huascarán Norte (May 31, 1970) into the Llanganuco valley (ID CB1, CB2) and Rio Santa valley (Evans et al. 2009) and of Lake Jircacocha (1941, ID CB16) in Cojup valley (Emmer and Juřicová 2017) do we have the direct age information (Fig. 3).

Morphological analysis

The ability of a landslide to create a dam depends on several characteristics of both the landslide and river valley systems. Deterministic approaches are often adopted to simulate the features comparison and predict evolutions. A common methodology in such analysis is the formulation of geomorphological indexes based on morphometrical parameters of the two involved systems, the river and the slope, including dam volume, valley width, and watershed area (Swanson et al. 1986; Ermini and Casagli 2003; Korup 2004; Dong et al. 2011; Peng and Zhang 2012). Landslide dam formation and stability predictions are not an easy task, due to the number of factors involved, and they are assessed through critical threshold index values. Critical index values dividing stability domains have usually a low predictive power and are often subject to regional conditions (e.g., Cui et al. 2009; Korup 2004; Strom 2013). Tacconi Stefanelli et al. (2016) proposed two geomorphological indexes to assess the formation and stability of the Italian dams.

These two indexes are the Morphological Obstruction Index (hereafter MOI)

$$MOI = \log V_l \Big/ W_v \tag{2}$$

and the Hydromorphological Dam Stability Index (hereafter HDSI)

$$HDSI = \log\left(\frac{V_l}{A_b \cdot S}\right) \tag{3}$$

where V_l is the landslide volume (m^3), W_v the valley width (m), A_b the catchment area of the blockage (km^2), and S is the local longitudinal slope of the river stretch (m/m). They are jointly used to carry

Fig. 3 **a** Upstream view of the lake of Llanganuco Baja (ID CB2) and the dam of Llanganuco Alta (ID CB1). **b** Picture across the former Jircacocha Lake (ID CB16)

out preliminary forecasting about formation and stability of landslide dams along river channels during emergency or planning activities. In a first stage of the procedure, MOI assesses whether the landslide may cause a complete valley obstruction or not. If a dam is formed, in a second stage, the HDSI assesses the dam stability. The two indexes show an improvement in the prediction effectiveness of formation and stability of Italian dams compared to other common indexes from the literature (e.g., Blockage Index and Annual Constriction Ratio from Swanson et al. 1986). The MOI bilogarithmic plot of landslide volume and valley width is divided into three different evolution domains: *non-formation*, *uncertain evolution*, and *formation* domains (Fig. 9). The *uncertain evolution* domain is bounded by two dashed lines, the lower *non-formation line* and the upper *formation line*. The former is the lower limit for the formed dams (both stable and unstable), while the latter is the upper bound of the not formed dams. For the HDSI plot, three main domains can be described as well: *instability*, *uncertain determination*, and *stability* domain (Fig. 11). In the first domain, only not formed or formed-unstable dams can be found. In the second domain, the dams evolution is uncertain and all the three evolution classes are present, while the last domain is formed only by formed-stable dams.

Results

Inventory and morphometry of dams and dammed lakes

For this paper, 51 cases (Fig. 1) have been identified along the Cordillera Blanca mountain range, in Huascarán National Park, Ancash Province, Peru.

Table 5 reports the surveyed information about the landslide dams inventory based on the database structure proposed in Table 1. A classification of the originating dams based on six main types of landslide movement as proposed by Cruden and Varnes (1996) is reported in the histogram of Fig. 4. The most common movement is the complex slide (41% of the total) that commonly is the result of a first movement consisting of a fall or slide of rock and/or debris, evolving into a flow of rock and/or debris. Individual flow and fall movements are also very common throughout the Cordillera Blanca Mountains with 20 and 18% of the total, respectively. Slide and slump are present with 14 and 8%, while it was not possible to identify topples or spread movements at our research scale.

Morphological characteristics of valleys and landslides in the Cordillera Blanca have a rather small variability. Concerning the landslide volume, in Fig. 5, almost all collected landslides (98%)

Table 5 The inventory of landslide dams from Cordillera Blanca, Peru

ID	Locality	Position	L. Mov.	V_l (m^3)	*d* type	V_d (m^3)	Q_d (m a.s.l.)	*d* Cond.	Evo.	W_v (m)	Catch. A (km^2)	*S* (°)	Lake cond.
CB1	Llanganuco Alta	209,923; 8,996,637	Fall-flow	20,274,000	IV	874,000	3853	CT1	FS	350	28.5	0.8	EX1
CB2	Llanganuco Baja	208,467; 8,995,382	Fall-flow	24,819,000	III	968,000	3839	CT1	FS	440	32.6	0.4	EX1
CB3		209,298; 9,007,307	Flow-fall	88,000	II		4386	CT1	FS	75	1.1	26.0	EX1
CB4		217,111; 9,009,345	Slide-fall	2,288,000	III		3916	CT2	FS	140	18.3	2.2	DS1
CB5		201,094; 9,023,151	Fall	2,283,000	IV	123,000	4086	CT2	FS	185	18.8	1.5	EX2
CB6		262,326; 8,911,760	Fall-flow	7,025,000	III	1,668,000	4735	CT1	FS	170	0.2	32.2	EX1
CB7		259,920; 8,893,846	Slump-flow	497,000	II	24,000	4440	CT1	FS	80	1.55	5.4	EX1
CB8		256,966; 8,913,998	Fall	2,161,000	III	176,000	4660	CT1	FS	135	0.6	10.7	EX1
CB9		244,096; 8,923,964	Slide-flow	17,593,000	IV	1,451,000	4006	CT1	FS	550	23.3	2.9	EX2
CB10		239,215; 8,953,308	Slump-flow	2,276,000	II	81,000	3965	CT2	FS	245	63	1.6	DS2
CB11		242,996; 8,922,604	Flow	10,380,000	III		3959	CT2	FS	300	25.1	1.4	DS2
CB12		247,384; 8,920,415	Slide-flow	1,956,000	II		4134	CT2	FS	230	7.5	1.1	DS2
CB13		259,542; 8,922,153	Slump	2,533,000	II	134,000	4020	CT2	FS	220	21.6	1.8	DS1
CB14		260,720; 8,923,822	Slump	1,451,000	II	150,000	3956	CT2	FS	85	29.9	1.4	DS1
CB15		232,341; 8,952,325	Fall	1,821,000	II		3990	CT2	FS	110	45.7	3.9	DS1
CB16	Jircacocha	233,458; 8,953,427	Fall	3,574,000	II	449,000	4095	BR1	FU	180	42	1.9	DS3
CB17		230,251; 8,967,176	Slump-flow	1,642,000	III		4216	CT2	FS	130	15.6	6.9	DS1
CB18		217,106; 8,986,285	Topple-fall-flow	24,104,000	III		3788	CT2	FS	365	29.3	1.1	DS2
CB19		203,604; 9,010,401	Fall-flow	11,100,000	III	490,000	3814	CT2	FS	240	18.7	1.2	DS1
CB20		258,117; 8,921,485	Slump	28,651,000	II		4078	CT2	FS	280	17.8	2.1	DS1
CB21		260,099; 8,922,605	Slide-flow	4,139,000	IV		3986	CT2	FS	230	28.1	1.5	DS1
CB22	Huecrucocha	223,666; 9,012,543	Slide	15,119,000	III	1,227,000		CT1	FS	170	15	2	EX1
CB23	Ichiccocha	204,791; 9,010,841	Flow	14,349,000	III	900,000	3862	BR2/CT2	FU	320	86	1.7	DS4
CB24	Jatuncocha	206,890; 9,011,691	Slow	16,625,000	III	2,332,000	3900	BR2/CT2	FU	340	72	6.8	EX2
CB25	Patarcocha	240,942; 8,981,098	Slide-fall	1,188,000	IV		3884	AS	FU	125	9.6	3.8	DS5
CB26		248,027; 8,978,651	Slide	1,164,000	II		4406	CT1	FS	90	1.1	6.9	EX1
CB27		252,345; 8,979,067	Slide	1,546,000	III		4243	CT2	FS	180	3.6	4.8	EX1
CB28	Tayancocha	246,718; 8,976,280	Slide	17,174,000	II	528,000	4114	CT1	FS	230	8.7	19.4	EX1
CB29	Purhuay	257,947; 8,969,627	Slide	50,000,000	II	9,322,000		CT1	FS	400	76	3.0	EX1
CB30		234,626; 8,954,848	Fall	799,000	IV			CT1	FS	185	39	1.9	EX2

Table 5 (continued)

ID	Locality	Position	L. Mov.	V_l (m^3)	*d* type	V_d (m^3)	Q_d (m a.s.l.)	*d* Cond.	Evo.	W_v (m)	Catch. A (km^2)	*S* (°)	Lake cond.
CB31	Jacacocha	253,092; 8,950,521	Slide-fall		II			CT1	FS	100	3	13.1	EX1
CB32		253,388; 8,950,010	Slide-fall		II			CT1	FS	90	2.3	8.6	EX1
CB33	Yanacocha	255,268; 8,945,568	Slide	7,351,000	III	506,000		CT1	FS	130	2.3	5.7	EX1
CB34	Querococha	243,932; 8,923,820	Flow	15,614,000	IV	473,000		CT2	FS	500	60.5	2.5	EX1
CB35	Querococha	243,932; 8,923,820	Flow		IV	473,000		CT2	FS	500		2.5	EX1
CB36	Gueshguecocha	246,171; 8,912,258	Slump	4,061,000	II	126,000		CT2	FS	160	31	0.8	EX1
CB37		250,220; 8,898,231	Flow	3,720,000	I	373,000		PBL, TE	NF	400	4.8	11.9	NF
CB38		247,189; 8,916,245	Flow	236,000	I	42,000		PBL	NF	260	7.5	3.5	NF
CB39		246,026; 8,930,842	Flow-fall	189,000	I	13,000		PBL	NF	250	2	8.9	NF
CB40		252,405; 8,942,833	Slump-flow	247,000	I	39,000		PBL	NF	140	41.5	1.0	NF
CB41		241,522; 8,937,736	Flow	2,754,000	I	196,000		PBL, TE	NF	215	28.6	4.4	NF
CB42		237,720; 8,943,972	Flow	324,000	I	59,000		PBL, TE	NF	190	36.3	1.6	NF
CB43		238,500; 8,948,297	Flow-fall	2,720,000	I	269,000		PBL	NF	185	23	1.3	NF
CB44		243,879; 8,954,638	Flow	2,747,000	I	90,000		PBL, TE	NF	190	12.6	5.5	NF
CB45		236,529; 8,956,617	Flow	3,247,000	I	209,000		PBL, TE	NF	200	25.7	2.9	NF
CB46		233,816; 8,953,903	Flow-fall	2,087,000	I	166,000		PBL, TE	NF	295	40.9	1.8	NF
CB47		230,712; 8,962,423	Flow-fall	408,000	I	33,000		PBL, TE	NF	165	35	3.0	NF
CB48		201,857; 9,001,704	Fall	353,000	I	12,000		PBL	NF	180	18.5	5.1	NF
CB49		202,962; 9,002,637	Fall	1,032,000	I	72,000		PBL	NF	220	12	4.5	NF
CB50		226,225; 8,967,690	Fall	2,375,000	II	317,000		PBL	NF	330	57.4	1.2	NF
CB51		224,633; 8,966,652	Fall	4,976,000	II		3470	CT2	FS	200	67.6	1.5	DS2

CT1, 2 slightly, strongly cut, *BR1, 2* breached, partially breached, *AS* artificially stabilized, *PBL* partial blockage, *TE* toe erosion, *FS* formed stable, *FU* formed-unstable, *NF* not formed, *EX1, 2* existing (generic), existing partially filled, *DS1,2,3,4,5* disappeared (generic), for spillway erosion, for dam collapse, for filling, and for man-made influence

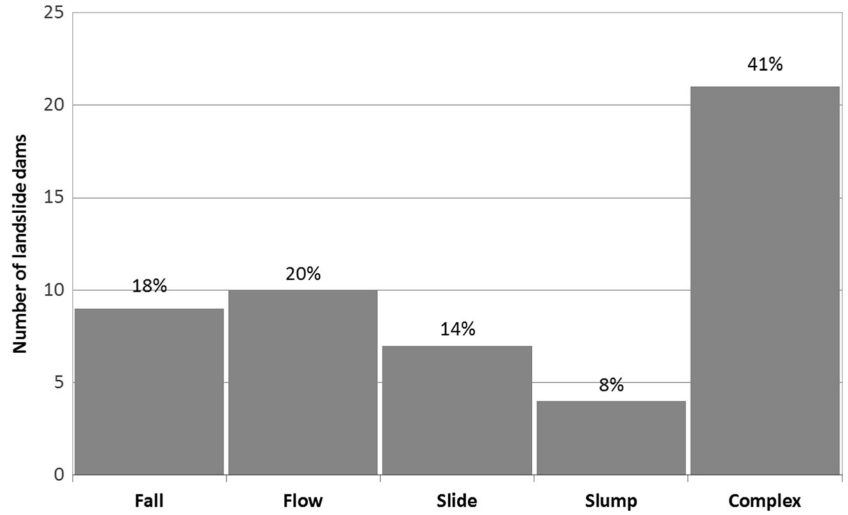

Fig. 4 Distribution of landslide dams in the Cordillera Blanca by type of landslide (according to classification from Cruden and Varnes 1996)

have a volume ranging from 10^6 to 10^8 m^3. More than half of the landslides have a volume of the order of 10^7 m^3. Moreover, as shown in Fig. 6, the valley width has regular distribution, ranging from 100 to 600 m, with the most frequent value between 200 and 300 m (66% of the total).

Concerning the classification of dam condition, most of the collected cases (64%, green in Fig. 7) are classified as formed-stable dams as they apparently never catastrophically failed or, for 5 cases (10% of the total), lakes located behind the dams were filled by sediments. Only four cases (8% of the total, red in Fig. 7) collapsed in historical time, or left clear signs of a past failure, and are classified as formed-unstable. The remaining 28% belong to not formed dams (blue in Fig. 7). According to the landslide dams geomorphological classification proposed by Costa and Schuster (1988), type II is the most common class with 32% of the total (Fig. 7). This is closely followed by types I and III with 26 and 28%, respectively, and type IV with 14% of the dataset. No dams belonging to types V and VI have been identified in the study area. Almost all of the not formed dams (13 out of 14) belong to the type I class.

Concerning the dammed lakes conditions, they can be existing, disappeared, or not formed lakes. Figure 8 shows that almost half of these lakes (41%) still exist and the remaining lakes are distributed between disappeared (31.4%) and not formed cases (27.5%). Unfortunately, half of the disappeared lakes (8 out to 16) are classified as "generic disappeared," because the lack of direct information and field surveys did not allow us to specify the cause with more detail. The remaining eight lakes disappeared primarily from spillway erosion (five cases) and one case for each of the remaining three possible mechanisms, which are dam collapse, filling, and man-made influence.

Morphological analysis of the Cordillera Blanca inventory and comparison with Italian dataset

The manual classification of the landslide dam evolution is then analyzed through some of the geomorphological indexes used on the Italian territory. For a clearer understanding of the morphological analysis results with the selected indexes, the analysis of the Cordillera Blanca database has been compared with that of the Italian landslide dams inventory. The Italian inventory was selected as a group comparison because it is a large available dataset, made of 300 collected cases, where the indexes were designed and tested already. Thus, Fig. 9 reports the MOI bilogarithmic plot of landslide volume and valley width of landslide dams in the Cordillera Blanca compared with the Italian cases (Tacconi Stefanelli et al. 2016). As the index purpose is the assessment of dam formation likelihood, in the interests of further clarity, in this figure, stable and unstable dams are identified as "formed dam." The diagram shows a very similar and comparable behavior of the two datasets. All the formed dams from Peru are grouped above the lower *non-formation* dashed line and all the not formed dams are below the upper continuous *formation* line. More than two thirds of formed and a quarter of not formed dams (73% and 29% of them respectively and 60% of the total) fall into the proposed *uncertain evolution* domain, encompassed by the two lines. Nevertheless, most of the not formed dams (71%) are correctly placed in the *non-formation* domain.

However, the MOI value distribution of the Cordillera Blanca dams does not completely match with the Italian data in Fig. 10. Here formed-stable and formed-unstable are displayed in different categories. Not formed and formed-unstable dams have similar behavior and are within the same boundaries set by Italian cases ($MOI < 3.00$ for *non-formation* domain and $3.00 < MOI < 4.60$ for *uncertain evolution* domain). Formed-stable dams from the Cordillera Blanca have a slightly different distribution and are more shifted toward instability, as they reach up to 3.07 of MOI value, even if they stay in the *formation* or *uncertain evolution* domains.

The results of the HDSI index application to the Cordillera Blanca river obstructions in Fig. 11 show something interesting as well. Not formed dams are not shown in the graphic as this index is used to assess the dam stability after their formation. The domains defined by the Italian dataset gather all the Peruvian formed dams correctly, except for one wrong formed-stable case (ID CB3) placed in the *instability* domain. The lower bound of the remaining stable dams in Peru has $HDSI > 5.77$, slightly above the value obtained by the Italian cases, equal to $HDSI > 5.74$. The similarity of the HDSI values over the two datasets may be

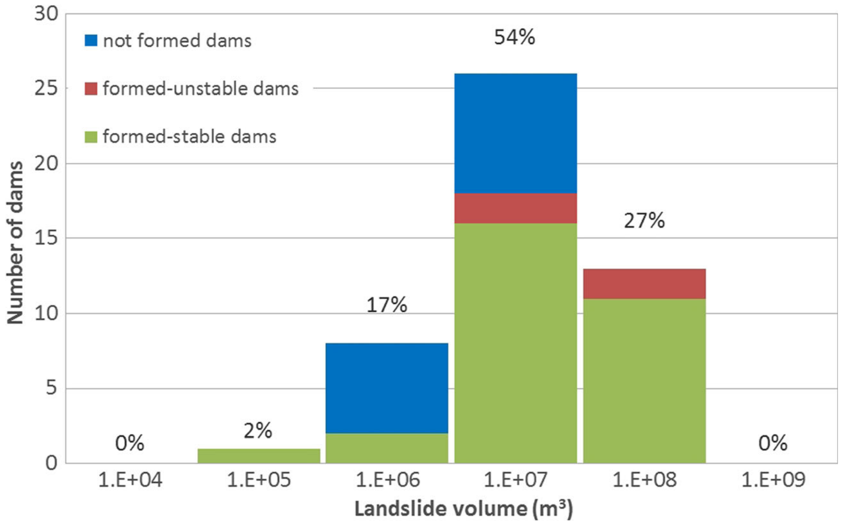

Fig. 5 Volume distribution of landslide dams in Cordillera Blanca according to the dam evolution

appreciated in Fig. 12, where the trends are similar, even if the Peruvian range of values is narrower, between 5.26 and 8.07, and more concentrated in the middle *uncertain determination* domain. The *uncertain determination* domain is wide, with 72% of the classified dams, and the *stability* domain contains 25% of the cases. The bigger difference between the two datasets arising from this figure is in the unbalanced distribution of the cases in the three evolution classes. While not formed, formed-unstable, and formed-stable cases are almost equally distributed in the Italian database, the lack of formed-unstable landslide dams in the Peruvian database (only four cases) is evident.

Specific evolutionary patterns of landslide-dammed lakes

This paper describes various landslide dams under current conditions; nevertheless, for the long-term geomorphological evolution, potential future changes need to be considered. In fact, in the whole mountain range (as well as in the dataset), landslide dams of different types, ages, and stages of evolution are found. They are also located in various parts of the valleys. Some of them could be considered as examples in a rather young stage of evolution while others bear signs of maturity and/or are filled by sediments.

Considering Fig. 6, it can be imagined that existing lakes could evolve, over time, into partly filled lakes and later disappearing due to complete filling by sediment. Filling of a lake basin by sediment infill is a gradual process, and lakes with stable dams may persist for long time periods until they are filled (Emmer et al. 2016). Other possible evolution could lead to the disappearance of a lake by dam collapse (failure) or by spillway erosion and breaching. Only two landslide dam failures which were followed by a significant lake outburst flood are documented from the Cordillera Blanca—(1) the 1941 dam failure of Lake Jircacocha in Cojup valley (ID CB16; Fig. 3b) and (2) the 2012 dam failure of Lake Artizon Bajo in Artizon valley (Santa Cruz), both caused by a flood wave from a lake outburst occurring upstream (Emmer and Juřicová 2017). Two modes of dam failures are distinguished: (1) partial dam failure (release of a part of retained water) and (2) complete dam failure (release of all water retained and lake disappearance). Dam failure can be triggered by dam body instability

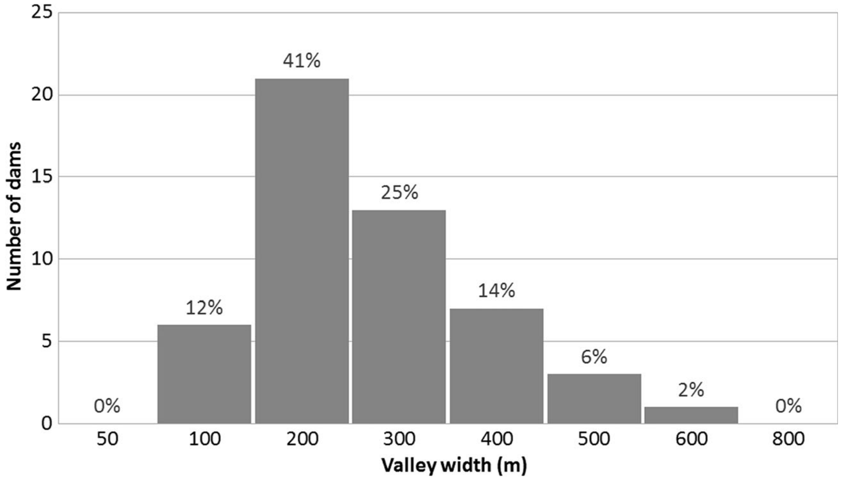

Fig. 6 Distribution of dammed valley width in Cordillera Blanca

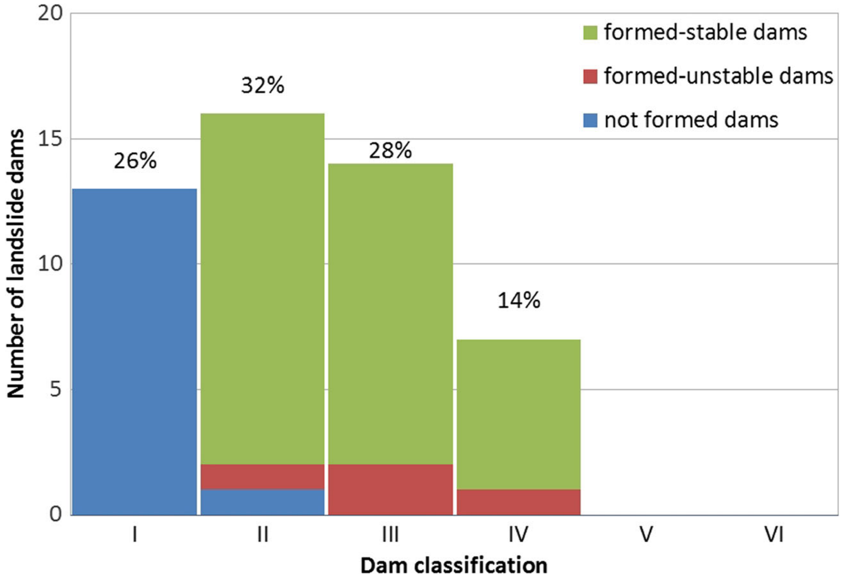

Fig. 7 Geomorphological classification of Cordillera Blanca landslide dams (Costa and Schuster 1988) and dam condition (Casagli and Ermini 1999)

or other external causes (also for dams classified as stable) such as an earthquake or an exceptional increase in discharge (lake outburst floods originating farther upstream). Specific evolutionary patterns of lakes dammed by debris cone are dam aggradation (e.g., dam aggradation of Lake Llanganuco Alto caused by slope movements induced by the earthquake in 1970). Dam aggradation may lead to a temporal or permanent increase in lake water level (volume). Dam aggradation and partial dam failure can be repeated several times until a new equilibrium drives the dam to maturity and the lake basin to filling or suffering a complete failure.

Discussion

The Cordillera Blanca mountain range is characterized by highly dissected relief resulting from the co-action of endogenic (tectonic) and exogenic (glacial, fluvial and gravitational) geomorphological processes. Glacial valleys are all characterized by a recent retreat of glaciers (e.g., Kaser 1999; Schauwecker et al. 2014) and very steep slopes. This common history is shown by a rather homogeneous distribution in the characteristics of Peruvian valleys and landslides in Figs. 5 and 6. The valley widths were conditioned by the dimension of glaciers, imposing small

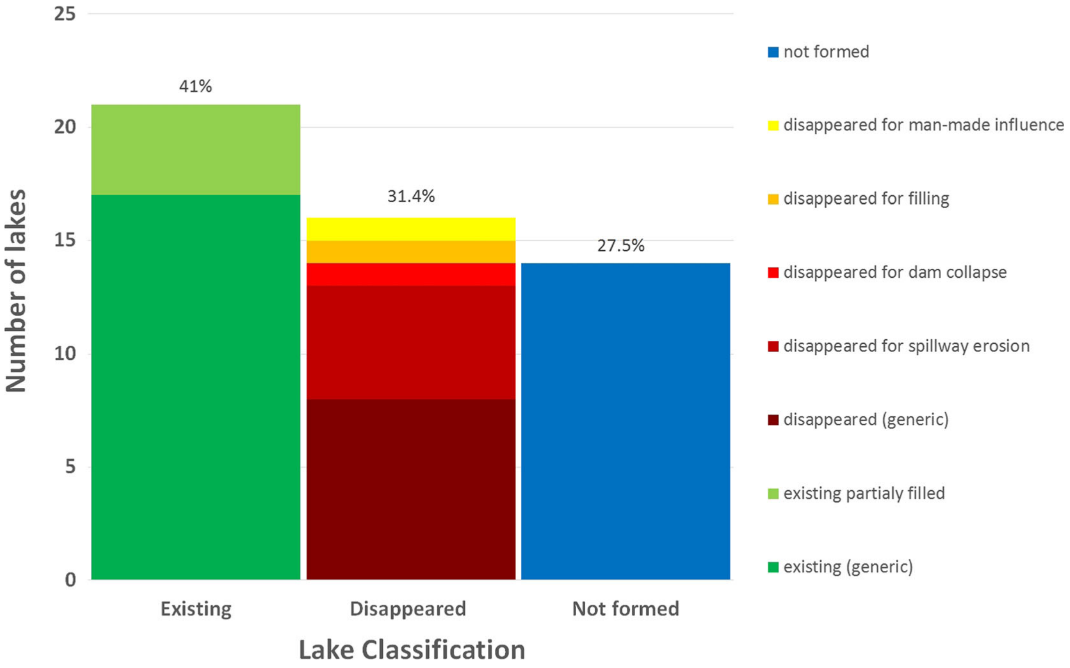

Fig. 8 Classification of dammed lakes in Cordillera Blanca, Peru, according to Casagli and Ermini (1999)

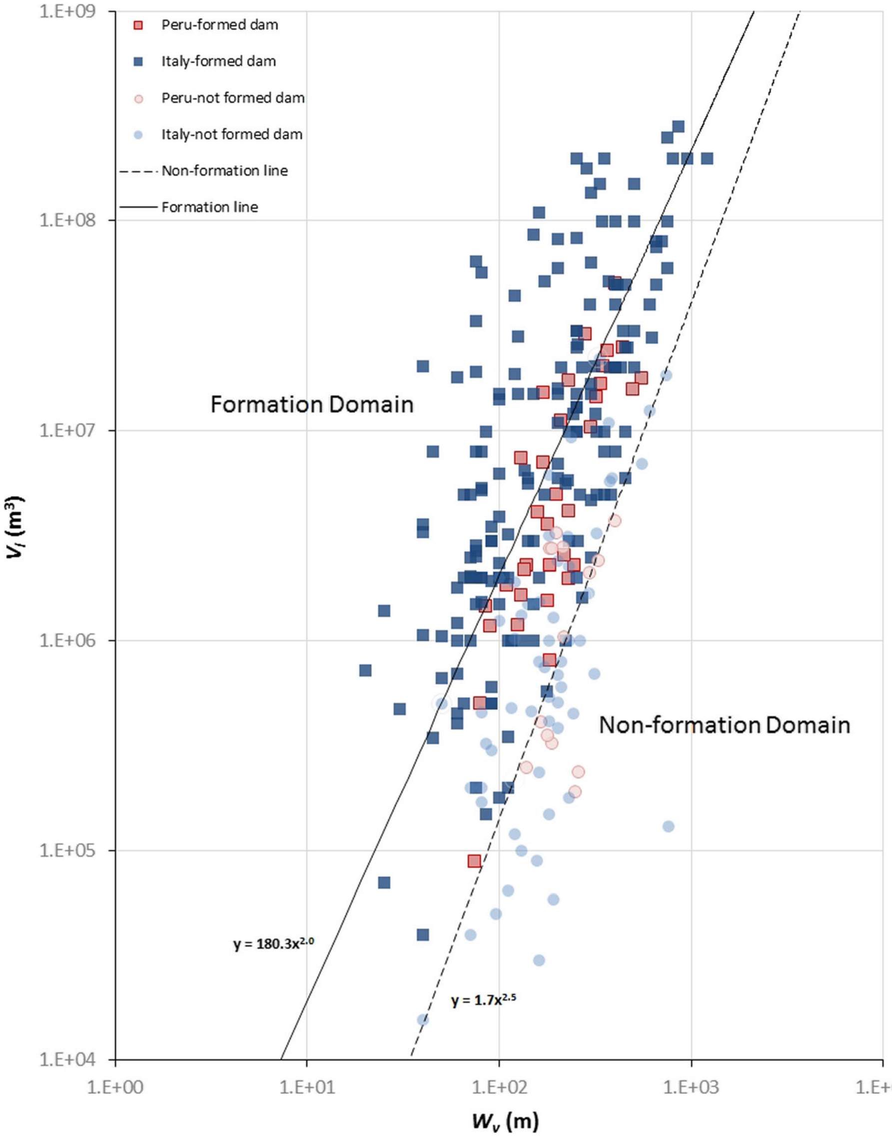

Fig. 9 Comparison of Peruvian and Italian Morphological Obstruction Index (MOI) values, where V_l is landslide volume and W_v valley width

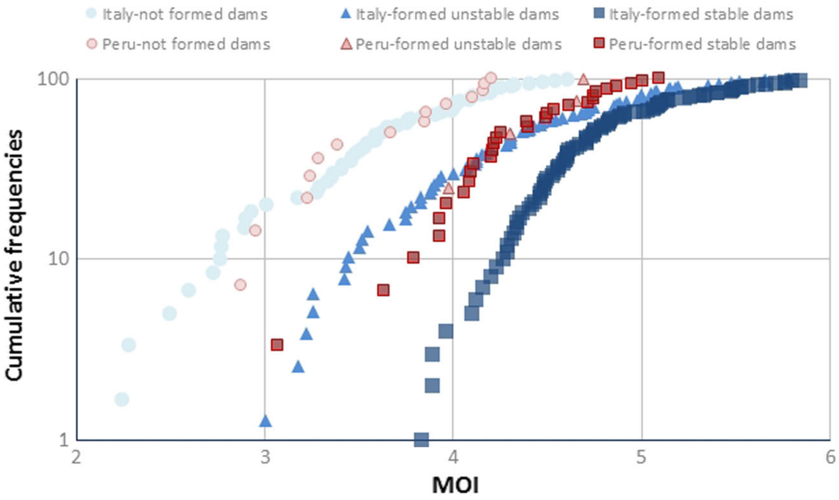

Fig. 10 Distribution of MOI values applied to the Peruvian landslide dams, distinguished by evolution classes, with the Italian cases

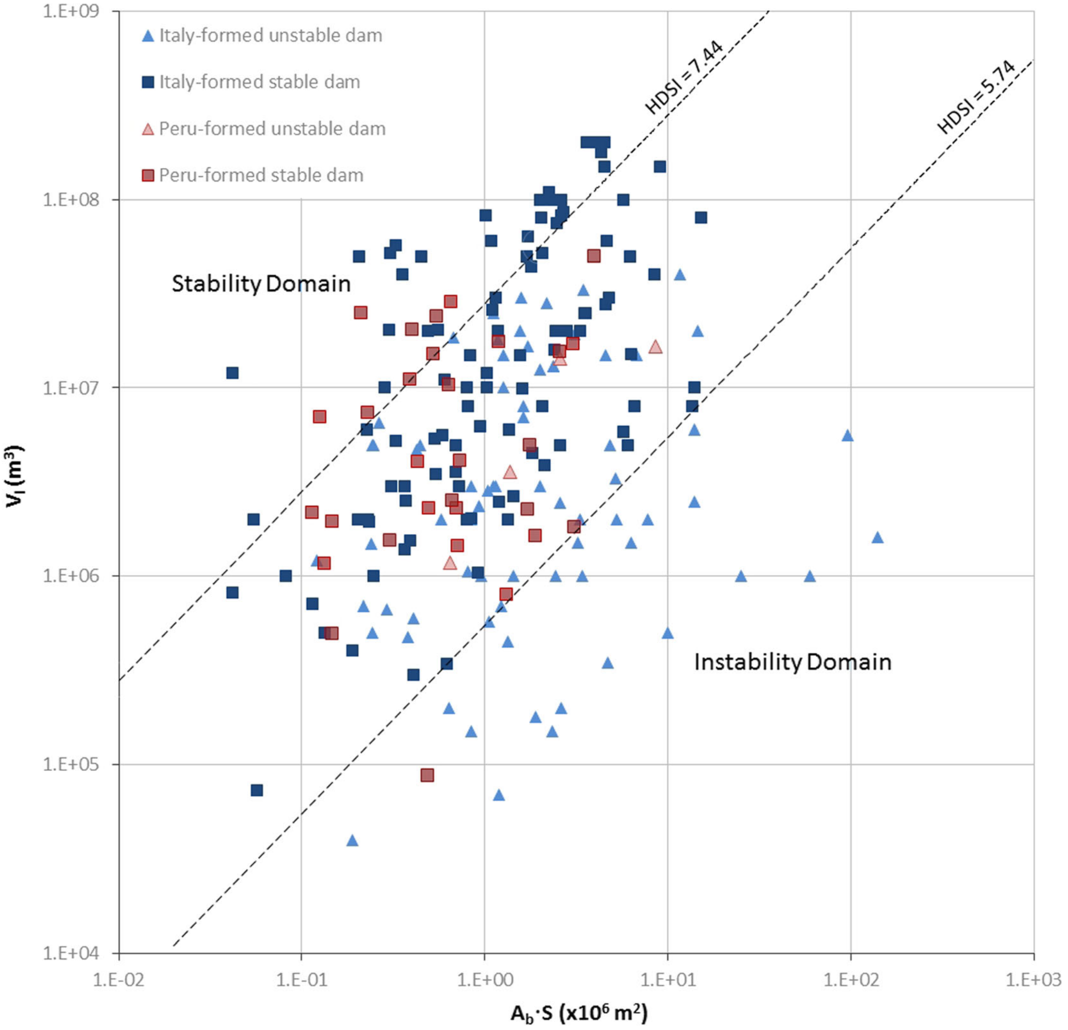

Fig. 11 Hydromorphological Dam Stability Index (HDSI) values distribution of the inventoried formed-stable Peruvian landslide dams compared with the Italian cases, where V_l is landslide volume, A_b catchment area, and S local river longitudinal slope

variability in the width distribution. The landslide volume distributions have an even lower variability ordered by the young and active tectonics of the mountain chain, providing periodical seismicity, steep morphology, and an almost monotonous lithology. The most common type of landslide movement, complex, falls, and flows, is also strictly correlated with the evolving

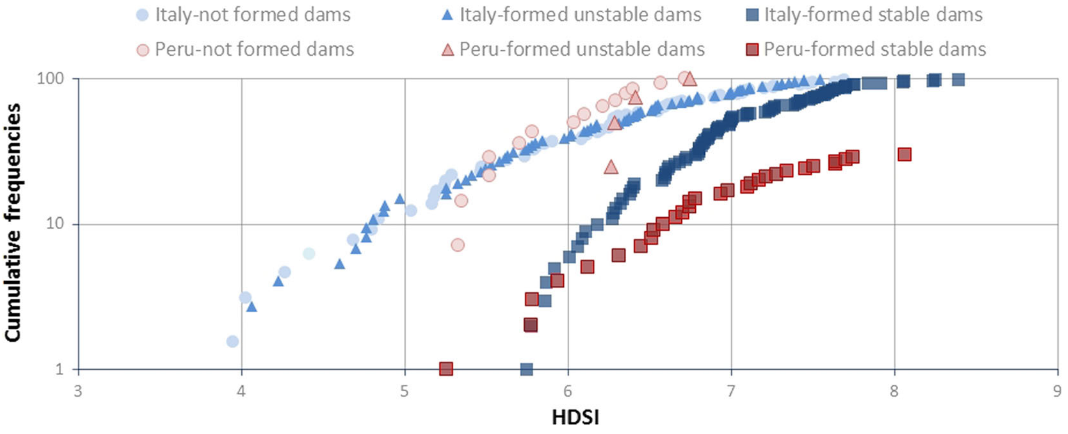

Fig. 12 Distribution of HDSI values applied to the Peruvian landslide dams, distinguished by evolution classes, with the Italian cases

environment. Falls are related to the very steep slope morphology of the mountain range of the Cordillera Blanca and their granitoid rocks, while flows are closely connected with the drainage channels of the glacial hanging valleys. The channels transfer a large amount of moraine material and coarser boulders from surrounding peaks to the main downstream valleys, accumulating huge volumes in large alluvial fans at the valley outlets.

The Cordillera Blanca and Italian datasets not only have their own features and differences, due to their different environments, but also have some similarities. The typical distribution of the morphometrical parameters that characterize landslides and river valleys in the Cordillera Blanca due to their environmental heritage is reflected in the results of the indexes application. The point cloud of the MOI distribution for dams from Peru is narrower and more compact compared to the Italian dams (Fig. 9). This reflects the general homogeneous dimensions of the Cordillera Blanca valleys and the almost monotonous distribution of landslides volume, due to more homogenous lithological and structural conditions against the more heterogeneous environments of Italian valleys. The Italian territory, which is much larger and characterized by greater variety of sedimentary, metamorphic, and igneous rocks, presents a wide variability in environment types and orogenic belts (Tacconi Stefanelli et al. 2015).

All data were correctly classified into the MOI domains and the index proved to be able to identify most of the not formed dams. Nevertheless, many of the formed dams fall into the *uncertain evolution* domain due to the small distribution range of the valleys width. The HDSI application allowed us to classify formed dams (Fig. 11) through the same Italian threshold values as well. In this analysis, the Peruvian formed-unstable class is represented by a small number of dams compared to the formed-stable class. This unbalanced distribution does not allow a complete evaluation of the HDSI effectiveness for this dataset, but nevertheless, all the formed Peruvian landslide dams have been correctly classified, except for one anomalous formed-stable case (ID CB3) that falls into the *instability* domain.

In general, the formed-stable dams in Peru have characteristics similar to Italian unstable cases, as most of them are scattered in the *uncertain determination* or *uncertain evolution* domain. This could be interpreted by hypothesizing that the dams within the Cordillera Blanca, even if classified as formed-stable, are in disequilibrium with their surrounding dynamic environment (continuous tectonic uplift followed by fluvial erosion) and need to be monitored. A larger dataset (especially for formed-unstable dams) could be considered more representative for description and comparison and could lead to a better interpretation. The other reason might be that they are younger and the process of slow destabilization is still under progress.

Conclusion

In this work, a database of 51 landslide dams in the Cordillera Blanca Mountains, Peru, is presented, comprehensive of the main important features and morphometrical parameters. All the information was achieved through direct (field survey) and indirect (analysis of topographic and remotely sensed data) survey techniques. The data were interpreted to study the main characteristics of the Cordillera Blanca landslide dams as well as the local environmental influence on them. A morphological analysis with recently developed indexes MOI and HDSI was carried out and compared with an Italian landslide dam inventory. The application of the morphological indexes to the newly proposed database produced positive classification outcomes, but slightly different with the compared Italian inventory. The differences between the two groups of data can be attributed to the climate and morphogenetic differences of the two regions. The high similarity between the results of the geomorphological indexes application on datasets coming from different geographical contexts, Italy and Peru, is an encouraging result for the indexes reliability. It bodes well on the quality of the information provided by the indexes and their potential application in different geographical areas.

Acknowledgements

This was possible thanks to the full cooperation of the staff of the ANA—Autoridad Nacional del Agua (National Water Authority) in Huaraz, the Peruvian national structure with control function of the glacial lakes, that allowed full access of their photo archive and library. The authors thank the two reviewers for very detailed comments on our initial manuscript, which led to a much improved revision.

Funding information AE thanks Ministry of Education, Youth, and Sports of CR within the framework of the National Sustainability Programme I (NPU I), Grant No. LO1415.

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