Mitigation measures preventing floods from landslide dams: analysis of pre- and post-hydrologic conditions upstream a seismic-induced landslide dam in Central Italy

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Abstract
The design of engineering measures during emergency phases is crucial in mitigating the river flow impacts on landslide dams, avoiding dam breaks and related downstream flooding. Man-made hydraulic facilities represent a possible mitigation strategy for reducing the occurrence of dam breaching by diverting river inflow. Semi-empirical equations published in the literature may help define the landslide dam evolution and design the discharge to be diverted into the hydraulic works assuring the dam’s stability. These approaches need to be carefully validated with case studies, an important step in evaluating the accuracy of predictive models. The work presents and discusses the pre- and post-seismic hydrologic conditions along the Nera River gorge focusing on the role of the pre-existing anthropic works in mitigating the impact of river discharge on the Sasso Pizzuto landslide dam triggered by the October 30, 2016 earthquake (Central Italy). Considering historical data, the upper part of the river catchment has experienced the highest discharge values during the landslide dam lifetime. The discriminant analysis approach of the hydro-geomorphometric characteristics supported the definition of the critical peak flow, avoiding the dam’s instability. Thanks to an upstream hydropower bypass, about 80% of the river discharge increase have been diverted into an underground pipeline built in 1928 to feed the Preci hydroelectric plant (located a few kilometers downstream of the landslide dam). The discriminant analysis model, developed in the literature on other landslides worldwide, had a good performance in managing the upstream river discharge of Sasso Pizzuto dam, expanding its validity on other landslide dams.

Keywords Landslide dam · Earthquakes · Flooding risk mitigation · River discharge

Introduction
Landslide dams that partially or entirely block rivers represent a very high hazard for the downstream fluvial reaches, especially in mountainous areas with deep, narrow valleys (e.g., Costa and Schuster 1988; Ermini and Casagli 2003; Hermanns et al. 2004; Korup and Tweed 2007; Evans et al. 2011; Fan et al. 2020). The failure of dams can produce destructive-type flash floods coupled with debris flows (Costa and Schuster 1988; Highland and Bobrowsky 2008; Perucca and Angillieri 2008; Zhou et al. 2013). Recent global surveys recorded about 779 landslide dams from 34 countries/regions (Wu et al. 2022). Among the landslide dam inventoried in the literature, rainfall events are the main triggering cause, followed by earthquakes and snowmelts (Ermini and Casagli 2003; Wu et al. 2022). High magnitude earthquakes are more frequently responsible for large damming than those triggered by rainfall events, probably due to large volumes of material displaced and accumulated along fluvial reaches (Tacconi Stefanelli et al. 2016). In this way, the stability of seismic-induced landslide dams is considered higher than landslide dams triggered by rainfall events (Ermini and Casagli 2003). In general, many landslides tend...
to be overtopped by river flows, failing after a short time (e.g., in a few days or weeks, Costa 1985). The landslide dam lifetime depends on several natural and anthropic factors such as dam size and geometry, geotechnical and hydrogeological characteristics of the landslide body material, rate of the river inflow to the impoundment, and engineering works controlling the water level and discharge, etc. (Cencetti et al. 2006). The drainage area upstream of the landslide dam plays an important role in understanding the long-term evolution of the river obstruction since it is a proxy for discharge (Argentin et al. 2021). The catchment area ($A_c$) is considered in most of the worldwide obstruction and stability indexes such as the Blockage Index, BI (Swanson et al. 1986), the Dimensionless Blockage Index, DBI (Casagli and Ermini 1999), the Basin Index, Ia (Korup 2004), and the Hydromorphological Dam Stability Index, HDSI (Tacconi Stefanelli et al. 2016). Ermini and Casagli (2003) reported that most landslide dams are stable for DBI values lower than 2.75 and unstable for DBI values higher than 3.08. According to Fan et al. (2020), the various geomorphometric stability indices proposed in the literature in assessing dam formation and stability can be helpful to predict the probability of dam formation reasonably well, but their application to longevity estimates requires further assessment. Nevertheless, Cencetti et al. (2020) showed as such indexes have to be identified with, and applied to, specific and restricted territories and cannot be generalized. Sometimes stability indexes are unreliable if used in emergencies to make a good decision to mitigate the flooding risk related to dam breaching (Liao et al. 2022; Fan et al. 2020). The design of engineering measures during emergency phases (e.g., diversion of inflow) requires a quantitative assessment of how much water to divert into the hydraulic works (Shi et al. 2017). Although practical experiences and case histories are published offering qualitative suggestions on mitigating landslide dam risks, quantitative studies on how to minimize dam-break risks with proper mitigation measures have seldom been carried out (e.g., Schuster and Evans 2011; Sattar and Konagai 2012). Quantitative studies require monitoring upstream inflow discharge (inflow, $Q_{in}$) during pre- and post-seismic sequence. Hancox et al. (2005) and Dunning and Armitage (2005) reported case studies showing examples of stable landslide dams affected by limited overflow conditions with equilibrium between $Q_{in}$ and $Q_{out}$ (downstream discharge). Zhou et al. (2019) experimentally illustrated—using a large flume model test—the effects of $Q_{in}$, $Q_{out}$ and bed erodibility on outburst flooding induced by landslide dam overtopping. The landslide material is undergone three stages with $Q_{out}/Q_{in}$ moving from $< 1$ (the landslide dam can reduce the water flow) to $= 1$ (landslide dam does not affect water flow), to $> 1$ (landslide dam can amplify the discharge). Among the stability indices available in the literature, an interesting approach was proposed by Dong et al. (2009, 2011), presenting some equations based on a large worldwide landslide dams dataset. The authors performed a discriminant analysis to determine the dominant variables (geomorphometric and hydrogeological) affecting the stability of a landslide dam, concluding that peak flow resulted in the most significant variable influencing landslide-dam stability. The equation proposed by Dong et al. (2009) has an added value compared to those based on geomorphometric factors alone that extend beyond the assessment of the landslide dam stability. When the upstream inflow data to the dam are available, the Dong et al. (2009) equation may help the discharge design be diverted into the hydraulic works so that the dam passes into the domain of stability. This approach could be particularly important in a high seismicity area, where the landslide dam may experience very high flow rates ($Q_{in}$) due to the mainshock, which may be unrelated to local weather and climate conditions. It is crucial because the peak flow can produce a progressive failure downstream of the landslide dam, often producing large-scale debris flows and floods. After high magnitude earthquakes, the hydrogeological properties of the river catchment—and consequently the river discharge—can increase in a few days due to the water pressure increase in the aquifer and permanent or semi-permanent variations of the properties of the hydrogeological system feeding the river (Rojestaczer et al. 1995; Geballe et al. 2011; Manga et al. 2012; Petitta et al. 2018; Sato et al. 2000; Di Matteo et al. 2020, 2021; Valigi et al. 2020; Mammoliti et al. 2022). In this framework, engineering measures have to be properly designed during emergency phases and inflow diversion can be used when man-made hydraulic facilities (e.g., reservoir or irrigation systems) are available upstream of the dam (Peng et al. 2014).

The present paper reports a case study of decision-making in mitigating the risks by engineering measures on a landslide dam along the Nera River produced by the 2016 seismic sequence in Central Italy. The pre- and post-seismic hydrological conditions along the Nera River gorge are presented, focusing on the role of the pre-existing hydro-electric diversion in mitigating the impact of the increasing river inflow. According to Shen et al. (2020), the actual inflow rate during the period of landslide dam formation is not usually recorded in historical cases; thus, the present study, thanks to continuous monitoring, aims to improve the knowledge of the stability of dams also taking into account the management of upstream discharge. The DBI index and the discriminant models proposed by Dong et al. (2009) are used to preliminarily check the landslide dam stability, also discussing their performance in minimizing dam-break risks.
Study area

Geological characteristics

The study area is located in the highest part of the Nera River catchment (Umbria-Marche Apennines, Central Italy), characterized by meso-cenozoic limestone formations of the Umbria-Marche stratigraphic sequence (Fig. 1). The base of Umbria-Marche sequence is characterized by the outcropping of the Calcare Massiccio formation (shallow-water carbonates) and Corniola formation (stratified micritic siliceous limestones), which are followed by a pelagic sequence hosting calcareous siliceous marly rocks (Rosso Ammonitico and Calcari Diasprigni formations). In the structural highs, these rocks have been replaced by the deposition of the Bugarone formation. The subsequent deposition of the Maiolica formation (stratified and fractured limestones) occurred on both structural highs and structural lows. Upward the sequence is characterized by the Marne a Fucoidi formation (marly-limestone rocks), Scaglia Bianca and Scaglia Rossa formations (stratified pelagic rocks), and Scaglia Variegata and Scaglia Cinerea formations (marls and marly limestones). In the north-western part of the catchment area outcrop marly units (Schlier and Bisciaro formations), while the siliciclastic Laga formation is mainly exposed in the eastern sector of the catchment area.

Fig. 1 Structural–geological map of the investigated area with the location of the mainshocks of the October 2016 seismic sequence (earthquakes 3, 4, and 5 in Table 1) and the seismic-induced Sasso Pizzuto rockfall. CM = Calcare Massiccio; CO = Corniola; BU = Bugarone; RA = Rosso Ammonitico; CD = Calcari Diasprigni; MA = Maiolica; MF = Marne a Fucoidi; SB = Scaglia Bianca; SR = Scaglia Rossa; SV = Scaglia Variegata; SC = Scaglia Cinerea; MU = Marly units; LF = Laga formation; QU = Quaternary units (fluvi-lacustrine deposits and talus)
The 2016 seismic sequence

The Apennine ridge in Central Italy is affected by medium–high seismicity, as documented by several historical events (Rovida et al. 2016). The last important seismic sequence occurred in 2016 with a series of moderate-to-large earthquakes activated, within a few months, along a 60-km-long Apenninic-trending normal-fault system (Chiaraluce et al. 2017). The seismic sequence culminated on October 30th, 2016, with the MW 6.5 mainshock (Fig. 1) due to the reactivation of the M. Vettore–M. Bove faults (VBF) (Chiaraluce et al. 2017; Villani et al. 2018; Brozzetti et al. 2019; Barchi et al. 2021). Table 1 shows the location and magnitude of the main earthquake that occurred in 2016 in Central Italy. Regarding the mainshock of October 30th 2016, the strong-motion network of INGV (http://ran.protezionecivile.it/IT/index.php?evid=345980) recorded 0.46 g at Castelsantangelo sul Nera stations (see Fig. 1 for location). The reactivation of seismogenic normal faults produced important subsidence (up to a value of about 0.35 m) in the western sector of the VBF (Valerio et al. 2018).

### Table 1 Mainshocks of the 2016–2017 seismic sequence (Mw > 5.0)

| Event | Date       | Magnitude (Mw) | Location         | Lat-long     |
|-------|------------|----------------|------------------|--------------|
| 1     | August 24, 2016 | 6.1            | Accumoli (AQ)    | 42.70 – 13.70 |
| 2     | August 24, 2016 | 5.3            | Norcia (PG)      | 42.79 – 13.15 |
| 3     | October 26, 2016 | 5.4            | Castelsantangelo sul Nera (MC) | 42.88 – 13.12 |
| 4     | October 26, 2016 | 5.9            | Visso (MC)       | 42.91 – 13.09 |
| 5     | October 30, 2016 | 6.5            | Norcia (PG)      | 42.83 – 13.11 |
| 6     | January 18, 2017 | 5.1            | Capitignano (AQ) | 42.55 – 13.28 |
| 7     | January 18, 2017 | 5.5            | Capitignano (AQ) | 42.53 – 13.28 |
| 8     | January 18, 2017 | 5.4            | Capitignano (AQ) | 42.50 – 13.28 |
| 9     | January 18, 2017 | 5.0            | Barete (AQ)      | 42.47 – 13.28 |

### Materials and methods

#### Landslide dam characteristics

The 2016 seismic sequence caused several seismic-induced landslides, many of which were rockfalls along the Nera River Gorge. The most impacting event occurred after the strongest shock of October 30, 2016 (MW 6.5, Fig. 1): the Sasso Pizzuto rockfall, probably the biggest and most disastrous, happened in the area during the last two centuries. This landslide developed in the Maiolica formation, which is highly fractured and outcropping along a steep slope (greater than 40°). The source area was surveyed by Romeo et al. (2017) with a TruPulse™ 200 laser ranger finder a few weeks after the mainshock when the seismic sequence was still ongoing. The survey evaluated the detached rock mass in about 50,000 m³ (Fig. 2a,b). Recently, Forte et al. (2021) carried out a remote structural analysis of the source area, highlighting three main joint sets with an average orientation of 75°/335° (J1), 63°/284° (J2), and 78°/106° (J3). Seismic shaking acted on a rock wedge and, after an initial slide, the rock mass developed into a rockfall. The rock wedge moved along the intersection of systems J1 and J2, which plunges at 60° (Forte et al. 2021). The rockfall produced a debris accumulation of about 70,000 m³, including the mobilized pre-existing talus along the slope (Romeo et al. 2017). A similar estimation has been made by Franke et al. (2018) by comparing pre-earthquake DTM developed from aerial LIDAR (captured by the Italian Ministry for Environment and Cultural Heritage in 2013), and post-earthquake model obtained with small unmanned aerial vehicle (UAV-based 3D DSM). The debris, composed of an aggregate of limestone boulders and soil, dammed the Nera River forming a small lake, having a surface area of about 2,000 m² (Fig. 2c), flooding the main corridor between Umbria and Marche regions (SP 209 road) that has been transformed into a water channel (Fig. 2d). It is interesting to note that the pre-existing fine soils mobilized by the debris movement produced an erodible bed behind the landslide dam. Figure 2e shows a schematic section of the landslide dam body with a maximum thickness of 15 m, five of which covered the SP 209 road.

#### River discharge data

Monitoring inflow values to the impoundment (Qin) during pre- and post-landslide dam occurrence is important to understand the phenomenon’s evolution and set the mitigation measures. The upper part of the Nera River catchment experienced a prolonged drought period in the months after the mainshock of October 30, 2016 (Di Matteo et al. 2021); despite this, the river discharge gradually increased due to co-seismic effects mainly involving the base limestone complex (Calcare Massiccio and Corniola formations, Fig. 1). It has been a significant phenomenon for the upper part of the Nera River basin as surface waters are mainly fed—during no recharge periods (e.g., during the dry season or prolonged droughts)—by limestone aquifers by a set of permanent linear springs (Boni et al. 1986). In this
framework, in the hydrological analysis and simulations, the groundwater contribution from fractured-karst aquifers needs to be carefully considered (Di Matteo et al. 2020). Pre- and post-seismic river discharge values were collected from the SIRMIP online monitoring network (Civil Protection Agency of Marche Region, Central Italy). The gauging station is located in the Visso village (RT-1317), about 1 km upstream of the landslide dam (Fig. 1).

Methods for checking the stability of landslide dams

The investigation of the landslide dam breach processes is important for the prediction of disasters. In the last decades many experiments—at both laboratory and field scale—and models have been proposed to explore breach processes of landslide dams under different hydro-geomorphometric conditions (e.g., Davies et al., 2007; Chang and Zhang 2010; Chen et al., 2015; Zhou et al. 2019; Zhong et al. 2020). Other authors have proposed semi-empirical relationships to define the stability of landslide dams by merging the already published inventories on landslide dams. Among these, one of the most used is the Dimensionless Blockage Index, DBI, which is based on geomorphometric factors, Eq. 1 (Ermini and Casagli 2003).

\[
DBI = \log \frac{H_d \cdot A_c}{V_d}
\]

where:

- \( A_c \) = catchment area (L²);
- \( H_d \) = dam height (L);
- \( V_d \) = dam volume (L³).
Dams with DBI < 2.75 will be classified as a stable dam, while those having DBI > 3.08 will be classified as an unstable dam.

Tabata et al. (2002), based on seventy-nine landslide-dam events that occurred in Japan, reported a list of sixteen hydro-geomorphometric variables \( x_i \) including, catchment area \( x_1 \), stream order \( x_2 \), mean flow \( x_3 \), peak flow \( x_4 \), upstream channel gradient \( x_5 \), downstream channel gradient \( x_6 \), landslide volume \( x_7 \), landslide area \( x_8 \), horizontal travel distance \( x_9 \), slope height \( x_{10} \), dam height \( x_{11} \), dam width \( x_{12} \), dam length \( x_{13} \), lake depth \( x_{14} \), lake area \( x_{15} \), and dam volume \( x_{16} \). Recently Dong et al. (2009, 2011) used a discriminant analysis to find a linear regression useful to separate two or more groups of objects with respect to these variables. Equation 2 shows the form of the discriminant function as reported in Dong et al. (2009), followed by a brief description of the physical origin and assumptions of the model.

\[
D = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_n x_n
\]

where:
- \( D = \) discriminant score (if \( D > 0 \) the landslide is categorized into the stable group while for \( D < 0 \) it will be placed into the unstable group);
- \( x_i = \) independent variable \((i = 1, 2, \ldots, n)\);
- \( b_i = \) unstandardized canonical coefficient of the discriminant function for the i-th variable \((i = 0, 1, 2, \ldots, n)\);
- \( n = \) number of independent variables.

The discriminant function assumes that no variable may be a linear combination of other variables (Klecka 1980); moreover, according to Korup (2004), the geomorphometric variables of landslide dams, except the stream order, are log-normal distributed. Using the widely used cross-validation technique to assess the quality of all of the proposed discriminant (Korup 2004), Dong et al. (2009) determined the significant variables \( x_i \) affecting the stability of a landslide dam considering forty-three well-documented landslide dams in Japan (Eq. 3). This equation has been obtained by checking the performance of sixty-eight models, each one with different log-transformed variable combinations (e.g., \( x_1, x_7, x_{11}, x_{13}; x_1, x_7, x_{11}, x_{14}; \text{etc.} \)).

\[
D = -2.94 \log(Q_p) - 4.58 \log(H_d) + 4.17 \log(W_d) + 2.39 \log(L_d) - 2.52
\]

where:
- \( Q_p = \) peak flow \((L^3/T)\);
- \( H_d = \) dam height \((L)\);
- \( W_d = \) dam width \((L)\);
- \( L_d = \) dam length \((L)\).

Among the relevant variables in the model, log-transformed peak flow resulted the most significant variable influencing landslide-dam stability and more than 88.4% of landslide dams analysed are correctly classified by Eq. 3 (Dong et al. 2009). Considering a worldwide dataset (eighty-four landslide dams), a model with three variables (Eq. 4), the same used for the DBI index, is presented with a prediction power of 70.1%. In this case log-transformed dam volume \( (V_d) \) resulted as the most significant variable influencing the stability of a landslide dam. The prediction by Eq. 4 resulted higher than that obtained by the DBI index (64.9%).

\[
D = -2.13 \log(A_c) - 4.08 \log(H_d) + 2.94 \log(V_d) + 4.09
\]

In our study, indices based on engineering geological factors (i.e., dam geotechnical properties), such as that recently proposed by Liao et al. (2022), were not used because reliable information was hard to collect in the required risk management timeframe (e.g., Fan et al. 2020).

**Results**

The stability of the landslide dam produced by the Sasso Pizzuto rockfall has been investigated using indices based on geomorphometric (size and shape of the dam and valley system) and hydrogeological factors (pertaining to the river and the catchment area). Applying equations based on the geomorphometric factors derived from a worldwide database (Eqs. 1, 4) indicates that the Sasso Pizzuto landslide dam falls within the instability domain. In detail, by considering \( A_c = 146*10^6 \) m\(^2\), \( H_d = 15 \) m, and \( V_d = 50.000 \) m\(^3\) (Romeo et al. 2017), a D value of \(-428\) is obtained using Eq. 4 \((D < 0)\), making the dam fall into the unstable domain. The application of DBI index (Eq. 1) gave a value of \(4.64\) \((D > 3.08)\), also confirming the instability. Some other information can be obtained by considering the hydrogeological conditions of the catchment underlying the landslide dam, including the analysis of upstream inflow data. The October 2016 seismic sequence deeply affected the interaction between groundwater and surface water, influencing the river discharge. The river discharge of the Nera River has risen in the days after the 2016 mainshocks, with the most significant effects occurring between 2016 and 2017 (Valigi et al. 2019; Di Matteo et al. 2021). The discharge increase has been produced by several causes, such as the water pressure increase and variations of permeability of the hydrogeological system feeding the Nera River (Di Matteo et al. 2020). Figure 3a shows the Nera River hydrograph recorded at the RT-1317 gauging station—located upstream of the landslide dam—for a selected time span (2016–2017 period), including pre- and post-seismic phases. A few months before the October 30 mainshock, another important earthquake occurred.

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(Accumoli, No. 5 in Table 1), about 40 km south-east from the study area. This earthquake produced a slight increase in river discharge (about 2 m$^3$/s), followed by a further sudden increase produced by the October 30, 2016 earthquake, which also triggered the Sasso Pizzuto rockfall. In the initial stages, the water flow was blocked by the landslide dam, increasing the water level, producing an overflow (overtopping) with a negligible amount flowing in the natural river bed, indicating that the hydraulic conductivity of the debris was low. After the October 26–30 seismic sequence, the river discharge gradually increased from 5.4 m$^3$/s to 9.21 m$^3$/s in about 20 days, values that the Nera River has never experienced in the past, at least among the available flow data (Fig. 3b). The definition of the peak flow rate that could have produced the dam’s failure was a challenge during the emergency phase affecting the upper part of the Nera River catchment because the evolution of river discharge over time was unknown in the days following the landslide. In this framework, the experiences gained in similar cases and the already published equations had of great help in supporting management decisions for mitigating the impact of river flow on the dam body. According to Eq. 3, the critical peak flow allowing the instability of the dam is about 7.8 m$^3$/s, a value much lower than the peak flow (Q$_p$) reached by the Nera River during the post-seismic phase (10.3 m$^3$/s, Fig. 3b). In detail, for the maximum peak flow value, the equation gives a value lower than zero (−0.37), making the landslide fall within the unstable group. Thanks to an upstream hydropower river diversion—managed by ERG Hydro Company—most of the discharge increase has been diverted into an underground pipeline built in 1928 for feeding the Preci hydropower plant (located a few km downstream of the landslide dam, Fig. 4). Due to the emergency phase and safety checks to the underground pipeline, the monitoring system did not measure the overall discharge diverted to the Preci’s hydropower in the first weeks after the October 30 earthquake (i.e., overflow is not measured). It can be deduced by looking at Fig. 3a as the flow rates in the tunnel are stationary at around 6 m$^3$/s, and the Q$_m$-Q$_n$ difference does not correspond to the diverted one. Despite this, the discharge values released towards the landslide dam were correctly measured. During the 2 weeks after the October 30 mainshock (No. 5 in Fig. 3a–b), the river flow towards the landslide dam (Q$_m$) has maintained at about 1.03 m$^3$/s, a value corresponding to the Minimum Vital Flow (MVF) for this river reach (PTA Marche 2010). From the middle of November 2022, Q$_m$ was gradually set to a maximum of about 1.8 m$^3$/s, representing about 17.5% of the peak flow induced by the seismic sequence (Q = 10.30 m$^3$/s Fig. 3b). The hydropower river diversion smoothed the river flow peak towards the landslide dam. During the 2017 river’s recession phase, the river discharge gradually decreased, and the release of water to the impoundment was restored to pre-earthquake conditions (approximately 1 m$^3$/s, Fig. 3a). It is interesting to point out that using the actual smoothed peak discharge obtained thanks to the Preci’s hydropower river diversion, the D value calculated by Eq. 3 becomes higher than zero (D = 1.8), making the landslide largely fall
into the stable group. Therefore, the mitigation effect, i.e., the reduction of the flow velocity and the erosional force on the landslide dam, was considerable, preserving the erosion of fine materials embedded into large boulders and making it stable throughout its life.

**Discussion**

The comprehension of landslide dam evolution requires the investigation of relationships that influence the interaction between the river and the landslide dam body. As highlighted in this study, the application of stability indices requires information which may be not available everywhere, and often their applicability in other regions needs to be carefully investigated by case studies. The need to verify existing empirical models with observations was also highlighted by Bo et al. (2015), studying the Tangjiashan landslide dam, the largest one formed by the 2018 Wenchuan earthquake in China (June 2002). Opting for the relevant factors is critical in analysing landslide dam stability because the selection of the factors influences the predictive competencies of various models. This step is necessary for disaster risk reduction and mitigation planning, as it also occurs for landslide susceptibility mapping (e.g., Donnini et al. 2020; Chen et al. 2021; Rafiei Sardooi et al. 2021; Meena et al. 2022). As documented for the Sasso Pizzuto landslide dam, without considering the effect of inflow rates on the dam body, it remains challenging to design the critical peak flow producing the dam breaching, which is helpful in the design of mitigation measures. This aspect has been remarked by Zhao et al. (2018), discussing the emergency mitigation plan for the Tangjiashan landslide dam. The experiments carried out by Zhou et al. (2019) highlighted that when an erodible bed exists behind the barrier, as for the Sasso Pizzuto landslide, the time to reach the overburden peak discharge is shorter for larger Qin. In these conditions, the discriminant analysis of the hydro-geomorphological characteristics proposed by Dong et al. (2009) provided first-hand information on managing the river discharge along the Nera River, expanding its validity on other landslide dams. Reducing the flow rate below 10 m³/s has been crucial for Sasso Pizzuto landslide. Similar results have been recently presented by Zheng et al. (2021), who highlighted, by investigating data of large inventoried landslide dams (58 events), a negative correlation between landslide dam stability and the inflow rate. In particular, to avoid overtopping phenomena, the inflow rate should not remain larger than 10 m³/s. The management strategy used for the Sasso Pizzuto provides the literature with new data in areas characterised by landslide dams and

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**Fig. 4** Location of the gauging station RT-1317 (SIRMIP, Civil Protection Agency of Marche Region, Central Italy) with the path of the historical tunnel used to diverge the Nera River towards the Preci’s hydropower station.
earthquake-induced influences on surface and subsurface hydrology, phenomena that have characterised major historical earthquakes, such as the 1999 Chi–Chi earthquake in Taiwan (Liu et al. 2018), the 2018 Hokkaido earthquake in Japan (Osanai et al. 2019), etc. Moreover, the diversion of inflow by the existing man-made hydraulic facility presented here has some similarities with other landslide dams, such as the Randa landslide dam formed by a large rock fall in 1991 in Vispa River, Switzerland, triggered by a snow-melt period with high water table (Sartori et al. 2003). As for Sasso Pizzuto, part of the river discharge was diverted into an existing hydroelectric facility, giving time to local authorities to construct an open-channel spillway across the dam (Bonnard 2006). Another example is reported by Zhang et al. (2015) and Xu et al. (2017): the Hongshiyan landslide-dammed lake (China), triggered by the 2014 Ludian earthquake, flooded a diversion tunnel located upstream of the dam built to feed the Hongshiyan hydropower station (located downstream the dam). In this case, a detailed study has been carried out to repurpose the tunnel as an emergency spillway to prevent breaching. The presence of hydroelectric derivation works upstream of the dam confirms that this technique remains one of the most decisive in safeguarding the infrastructure and populations during the emergency phase. As for other landslides worldwide, river diversion should be considered a temporary treatment, which does not eliminate the disaster risks (e.g., Xu et al. 2017). Therefore, some subsequent treatments are necessary, which require longer implementation times. The hydroelectric diversion tunnel upstream of the Sasso Pizzuto landslide dam allowed engineering works to be designed and constructed 14 months after the 2016 earthquake in Central Italy. The SP 209 road was re-opened in February 2018, removing the accumulated debris in the riverbed, restoring the river flow to its original course, and protecting the landslide slope by flexible ring net barriers and reinforced earth embankments (ANAS 2018).

Conclusions

Landslides caused by earthquakes often block rivers in mountainous areas, forming landslide dams; their stability is affected by geometrical, geotechnical, and hydrological parameters. Although different engineering measures can be built ad hoc in the days/months after the landslide triggering to control the water level and the river discharge, pre-existing hydraulic works can be helpful reduce dam breaching floods. The case study highlights how hydraulic works built about a century ago play a fundamental role in protecting against hydraulic risk in high seismicity areas, such as the Central Apennines. In an overall risk assessment, the environmental aspects of river diversions, which are very important, must be analysed, considering the hydraulic risk. As documented, the peak flow of Nera River after the 2016 seismic sequence reached values much higher than those produced by the inflow–outflow processes related to local weather and climate conditions. The mitigation effect on the Sasso Pizzuto impoundment was considerable, with a reduction of about 80% of the peak discharge; the dam-break flood did not occur without impacts on people and property downstream. Although the geomorphological indices seem to classify the evolution of the Sasso Pizzuto dam correctly, the model proposed by Dong et al. (2009) based on geomorphometric and hydrogeological factors had a good performance for managing the river discharge for hazard mitigation. Concluding, the present study helps to validate some of the existing approaches to evaluate landslide dam stability, which allows the design of emergency responses in high seismicity areas where surface-water and groundwater changes occur.

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Declarations

Competing interests  The authors have no relevant financial or non-financial interests to disclose.

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