

Article

Dynamic Evolution of the Lacul Fără Nume Landslide Dam in the Eastern Carpathians: A Rare Recurrent Geomorphic System Characterized by Repeated Damming–Breaching Cycles

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Abstract

The Lacul fără nume landslide dam in the Vrancea Mountains (Romania) represents a unique example of a dynamic landslide dam system characterized by recurrent damming–breaching cycles. Through the combined use of remote sensing, field investigations, and historical reconstruction, eight such cycles were documented over a period of 49 years. To the best of current knowledge, this is one of the few documented landslide dams reported in the scientific literature that exhibits frequent damming–breaching episodes involving repeated dam failure, renewed slope instability, and subsequent re-damming with renewed lake impoundment over comparatively short timescales. The observed persistence and spatial extent of the associated lake are highly variable, ranging from 12 days to almost 10 years and from 23,920 m² to 82,610 m², respectively. Antecedent precipitation was frequently elevated prior to lake state transitions, but a seasonally constrained Monte Carlo analysis showed no significant departure from the climatic background, while numerous intense rainfall periods occurred without documented transitions. Similarly, no systematic temporal association was identified between recurrent lake state transitions and regional seismicity, although the initial dam formation coincided with the 1977 Mw 7.4 Vrancea earthquake. These findings suggest that precipitation conditions and seismicity alone cannot explain the recurrent damming and drainage, which likely result from interactions between hydrometeorological forcing, geomorphic processes, and human influences. Taken together, the results and the proposed conceptual model demonstrate that debris-flow-generated landslide dams can evolve into persistent and dynamic geomorphic systems capable of posing recurring hazards over multiple decades.

Keywords: landslide dams; GIS; remote sensing; geohazards; recurrent damming



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1. Introduction

Landslides that obstruct river channels and form dams are an important natural hazard due to their potential for sudden failure [1] and subsequent downstream flooding [2]. The resulting socio-economic and environmental impacts of landslide dams—such as damage to infrastructure and settlements or the modification of drainage systems—highlight the need for detailed process understanding regarding their formation, failure potential, and

occurrence patterns as a basis to improve hazard mitigation strategies as well as emergency responses [3,4].

In general, landslide dams form when the deposits of mass movements partially or completely block the watercourses of drainage systems [5,6]. These obstructions may directly result from rock slides, debris slides, and earth slides [7] or an interaction of those with other geomorphic landforms [8]. In Romania, the Eastern Carpathians are particularly susceptible to landslide dam formation, especially within their flysch lithology, which typically comprises highly fractured sequences of sandstones, carbonates interbedded with mud, or claystones that in some cases show unfavorable fracture networks, such as joint planes parallel to the slope surface [9]. Furthermore, steep slopes, narrow valleys, active geomorphological processes and anthropogenic interference such as deforestation, road cuts and mining activities are promoting factors for landslide dam formation [10,11]. Within the flysch zone of the Eastern Carpathians, several landslide dams occur in remote areas, generally producing limited impacts. However, some events have affected infrastructure and forested areas, while historical records document both temporary and long-lasting landslide-dammed lakes [11–17].

While most of the landslide dams in Romania either retained their associated lakes due to stabilization or lost their impoundments through breaching processes, the Lacul fără nume landslide dam shows an extraordinary behavior of repeated damming and breaching episodes. Case studies documenting recurrent river-damming landslides originating from the same slope are rare in the scientific literature, with the majority of studies implicitly treating landslide dams as single-event phenomena. The most prominent examples of recurring landslide dams in recent times are the Tangjiawan landslide blocking the Dubei river in 2008 and 2016 [18], the Jiangda landslide damming the Jinsha River twice in 2018 [19,20], and the triple failure of the Danan river landslide dam in 2021 [21]. Another historic example is given by Ermini et al. (2006) [22] with a landslide dam in the Passirio river basin where, between 1419 and 1774, the dam went through six failures that led to repeated blockages of its associated river channel. Guo et al. (2020) [23] also reports a total of eight damming events at the Yigong landslide over the past six millennia, indicating sub-millennia recurrence intervals. However, none of these reported cases match the frequency of damming–breaching cycles observed at the Lacul fără nume landslide dam. Most documented examples exhibit only a limited number of such cycles. Although the Passirio River blockage and the landslide dams at Yigong represent notable examples of recurrent landslide damming, with several damming–breaching episodes occurring over centuries and millennia, respectively, the Lacul fără nume landslide dam is distinguished by exhibiting multiple recurrent cycles within only a few decades. To the best of current knowledge, it represents a rare example of a landslide dam functioning as a dynamic geomorphic system characterized by repeated dam failure, renewed slope instability, and subsequent re-damming with renewed lake impoundment (Figure 1) over comparatively short timescales. Owing to the rarity of such systems and the limited number of comparable cases, the mechanisms controlling their recurrent formation, persistence, and breaching behavior remain poorly understood.

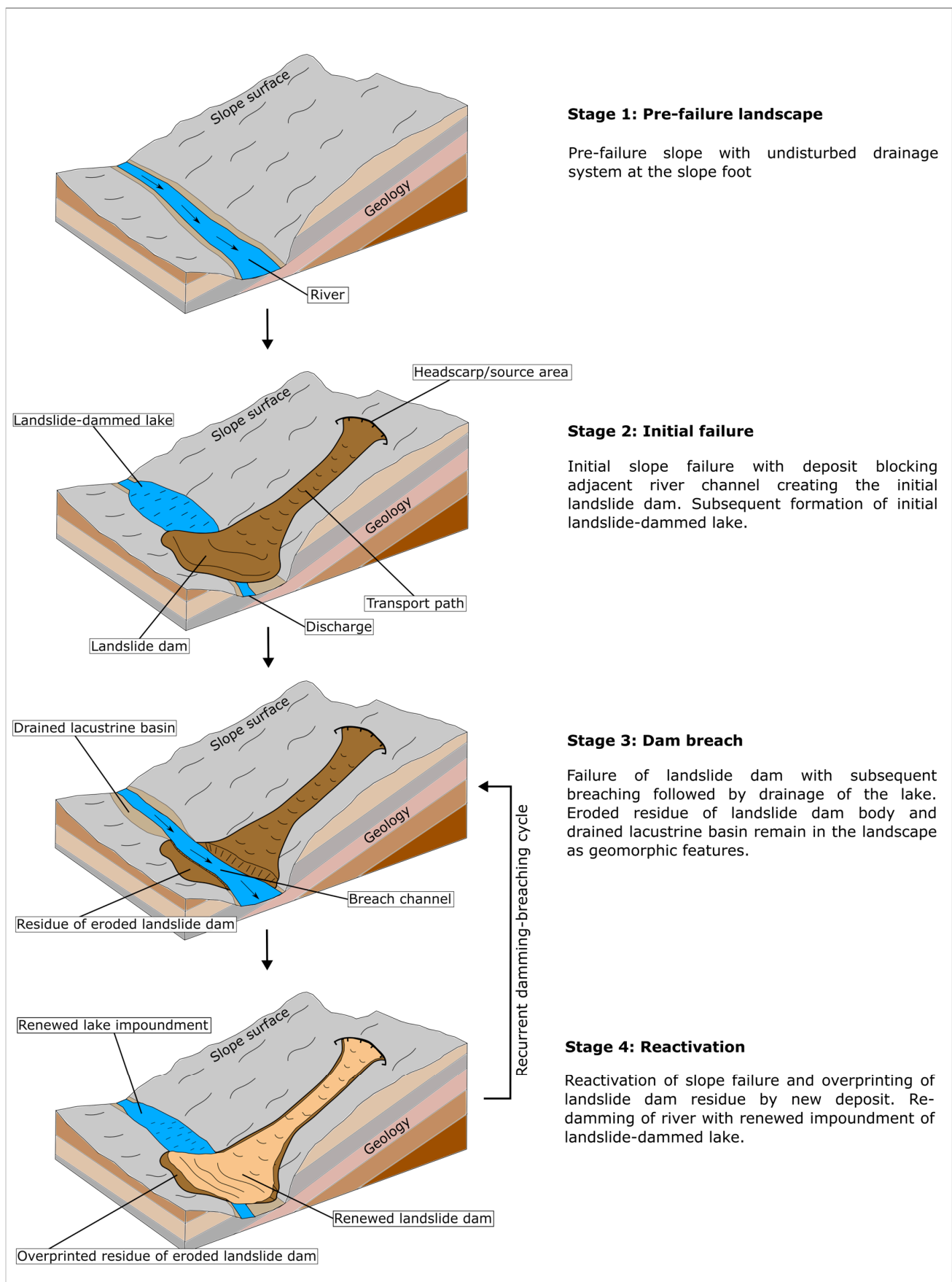


Figure 1. Conceptual model of dynamic damming–breaching cycles of recurrent landslide dam systems, as observed at the Lacul fără nume landslide dam, with geomorphic features annotated.

Consequently, the Lacul fără nume landslide dam provides a rare natural laboratory to document and analyze the long-term evolution of a recurrent landslide dam system through multiple damming–breaching cycles. To improve the process understanding of recurrent landslide dams, this study addresses the following four research questions:

- Can the long-term evolution of the Lacul fără nume landslide dam since its initial formation in 1977 be reconstructed from historical maps, remote sensing imagery, and field observations?
- Does the site represent an exemplary case of a landslide dam that developed into a recurrent geomorphic system characterized by repeated damming–breaching cycles?
- To what extent are the precipitation conditions and the seismicity in the area associated with observed transitions between dammed and drained states?
- How are the recurrent formation and drainage of the landslide dam related to external forcing and the inherited geomorphic configuration of the landslide system?

2. Materials and Methods

2.1. Study Site

Lacul fără nume is situated on the Zăbala River in the Vrancea Mountains of the Eastern Carpathians. The landslide dam drains a catchment of 131.2 km², one of the largest catchments associated with a landslide-dammed lake in Romania (Figure 2a) [12]. At the downstream margin of this catchment, debris flows are frequently delivered from a 0.14 km² scarp area with a maximum crown elevation of 1200 m (a.s.l.). From here, mobilized material travels downslope through a 1400 m long transportation zone until reaching the valley floor at an elevation of 900 m (a.s.l.), resulting in a maximum drop height of 300 m (Figures 2b and 3a). The maximum extension of the resulting landslide dam was documented in 2005 with a width of 220 m and a length of 90 m. During this stage, the impounded lake also reached its maximum observed extent, covering an area of 82,610 m². At the time of this study, the dam is breached and the associated lake completely drained (Figure 3b). Field measurements of the dam residue indicate a maximum dam height of 5 m. Assuming a simplified wedge-shaped geometry, the dam volume was estimated from the measured maximum surface area of 12,570 m² and an approximate maximum dam height of 5 m, yielding a volume of approximately 31,425 m³. Applying these geometric parameters to the Dimensionless Blockage Index (DBI) yields a value of 4.32, classifying the dam as unstable according to the thresholds proposed by Ermini and Casagli (2003) [24] and Tacconi Stefanelli et al. (2016) [25].

The study area is underlain by units mapped as PG1-2 on the Geological Map of Romania provided by the Geological Institute of Romania, corresponding to Lower-Middle Paleogene deposits, which in the Eastern Carpathians are represented by sedimentary flysch sequences. Field investigations indicate that the landslide dam material consists of a poorly sorted, matrix-supported debris flow deposit derived from the local flysch lithology. Structurally, the material contains angular to subangular clasts embedded in a fine-grained matrix comprising clay, silt, and sand (Figure 2c). Characteristic of debris flow deposits, the dam material exhibits neither sorting nor stratification and instead displays a chaotic internal structure. While scattered coarse clasts may locally form zones of elevated permeability, the overall abundance of fine-grained material suggests a low bulk permeability of the dam body, as also observed in other landslide dams developed within the same lithological unit [9,11].

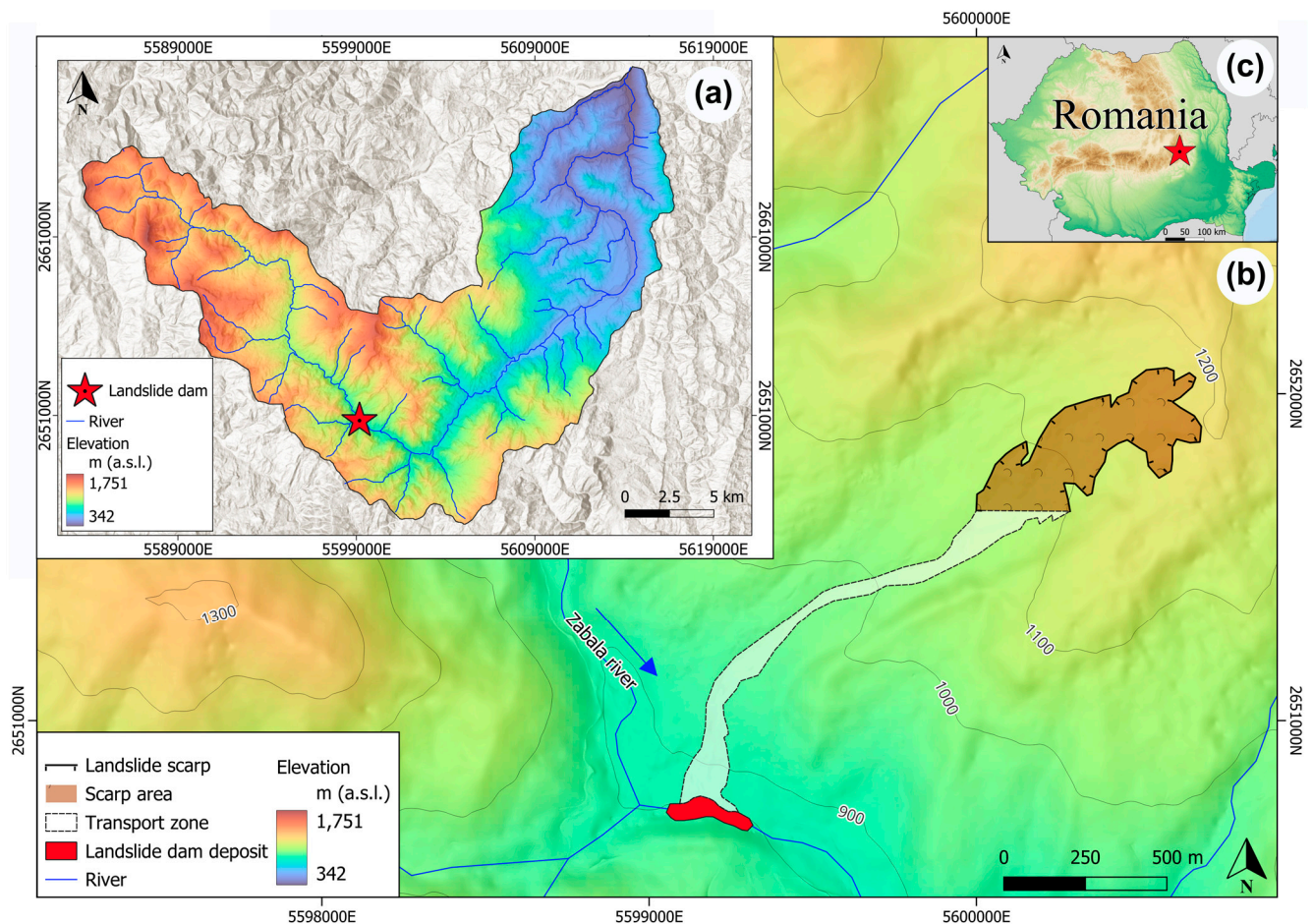


Figure 2. Geographical overview of the study area. Inset (a) shows the position of the landslide dam within the catchment of the Zăbala River. Main map (b) illustrates geomorphic features of the landslide dam and associated slope instability derived from a local DEM and optical satellite imagery. Inset (c) shows the position of the study area within the Eastern Carpathians. Data: (a,b) ESRI World Hillshade (Basemap); (c) SRTM30 Colored by terrestriis (Basemap). Projection: EPSG: 3035.

2.2. Data Acquisition and Processing

The coherent chronology reconstruction of the Lacul fără nume landslide dam from its initial formation in 1977 to its current form requires a combination of historic and modern satellite imagery as well as topographic sketches and accounts of the local population. The earliest data available is given by the now declassified imagery of the CORONA and HEXAGON programs, which provide limited photographic information about the study area from 1969 to 1983. While these programs produced numerous images of the Eastern Carpathians, only three scenes provide sufficient image quality to extract valuable information for the present study. Further information is given by a topographic map (scale 1:25,000, Stereo 70 projection) obtained from the first available field investigation in 1978 provided by the Romanian Topographic Directorate (Direcția Topografică Română).

From 1999 onwards, the Landsat satellite program has provided more frequent and continuous coverage of the study area, shifting the focus of the investigation from reconstruction to monitoring. The most recent development (2015–2026) of the Lacul fără nume landslide dam was monitored by using mainly a combination of Landsat 8, Sentinel-2 and PlanetScope data. A detailed list of the data series and utilized satellite imagery is given in (Table 1).

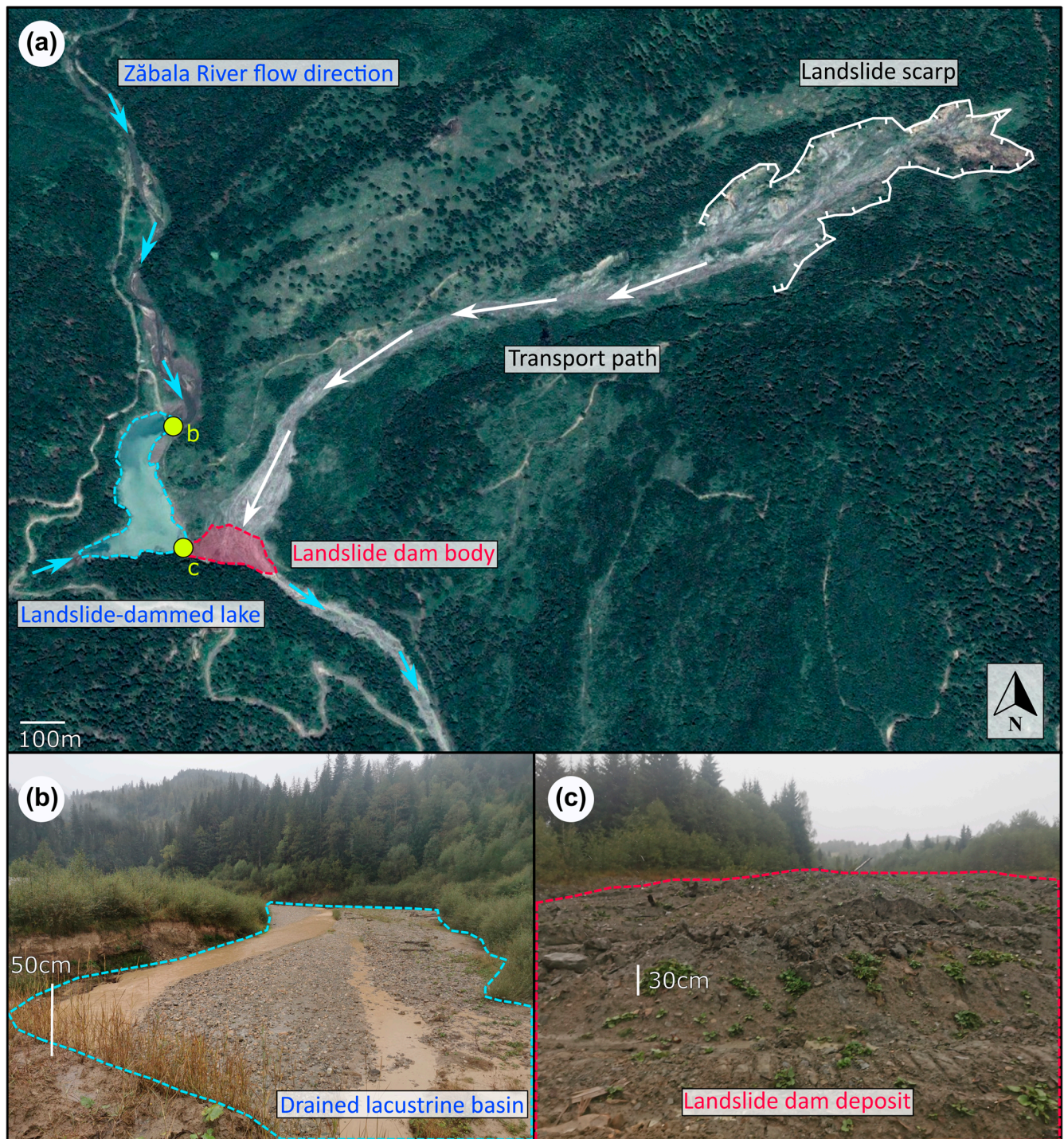


Figure 3. Morphological features of the Lacul fără nume landslide dam: (a) Satellite image with annotated features. The green circles mark the camera positions of the images shown in insets (b) and (c). Inset (b) shows a view in the downstream direction of the drained lacustrine basin in its current state, and inset (c) shows the upstream side of the remains of the currently breached landslide dam deposit. Data: (a) Google Earth Pro 7.3.6.9796, Imagery Date 19 June 2011, Maxar Technologies, modified; (b,c) photos by Mihai-Pintilie (2025).

The collected data was scanned and curated to identify episodes of lake presence or absence as proxies for river blockages or breaching stages. In cases where lake presence or absence was not clearly distinguishable based on natural colored images, the Modified Normalized Difference Water Index (MNDWI) [26] was calculated from the green and

shortwave infrared spectral bands. Inspection of the MNDWI images showed that open water consistently exhibited values close to zero, whereas the adjacent shoreline typically produced values below -0.35 . Based on this observation, cells with values greater than -0.1 were used to delineate the lake water body. The resulting lake extensions were subsequently verified by visual comparison with the corresponding satellite imagery to ensure agreement with the visible shoreline. Timespans of extensive snow coverage were excluded from the analysis since the snow masks the alluvial plane, which prevents a differentiation between underlying lake and river channel. Morphometric measurement, such as lake area and dam dimensions, were inventoried for every lake state transition.

Table 1. Data series of images used for chronology reconstruction and monitoring of recurrent landslide damming.

Year/Timespan	Data Source	Sensor	Resolution (m)
1969	CORONA KH-4 Satellite	Analog camera	~5
1978	Topographic map	-	-
1980	HEXAGON KH-9 Satellite	Analog camera	~5
1983	HEXAGON KH-9 Satellite	Analog camera	~5
1999–2013	Landsat 7	ETM+	30 (15)
2013–2026	Landsat 8	OLI/TIRS	30 (15)
2015–2026	Sentinel 2	MSI	10
2015–2026	PlanetScope Dove	MSI	~5–3

2.3. Precipitation and Seismic Data Analysis

The identified lake state transitions were compared with precipitation data from the Lăcăuți station 20 km northwest of the study area to explore heavy rainfall events as a possible trigger mechanism. For this, antecedent precipitation was quantified to evaluate the potential hydrological forcing associated with landslide-dam formation and drainage events. Previous studies have shown that antecedent rainfall influences slope stability over multiple temporal scales and that the appropriate accumulation period depends on the local hydrological and geological setting [27–29]. Daily precipitation data were used to calculate rolling cumulative sums over 3-, 7-, 14-, and 30-day windows preceding each event. These four windows were chosen to represent different temporal scales of hydrological forcing. The 3-day window is an indicator for short-term rainfall capable of triggering rapid slope reactivation. The 7-day window represents cumulative rainfall over approximately one week that is accounting for prolonged storm sequences. Intermediate antecedent moisture conditions that are capable of influencing groundwater recharge or pore-water pressure development are represented by the 14-day window. Finally, the 30-day window investigates long-term hydrological conditions that may predispose the slope to renewed failure. A 1-day window was not considered because the timing of dam formation and drainage derived from satellite imagery cannot generally be constrained to a single day (see Section 4.3) and because isolated daily rainfall is less representative of antecedent hydrological conditions. Conversely, accumulation periods substantially longer than 30 days increasingly reflect seasonal climatic variability rather than the hydrological conditions directly preceding individual formation or drainage events. For a given event date, antecedent precipitation was defined as the sum of daily precipitation over the preceding days.

To place event-specific values into a climatological context, empirical distributions of antecedent precipitation were derived from the complete time series by computing rolling sums for all days in the dataset. Event values were then compared to these distributions to determine their percentile rank, providing a measure of how typical or extreme the antecedent conditions were relative to long-term variability. Events with uncertain timing

(i.e., only year known) were excluded from the analysis to avoid seasonal bias. Based on percentile thresholds, antecedent conditions were classified into categories ranging from normal (<50th percentile) to extreme (>95th percentile).

To evaluate whether extreme precipitation alone was sufficient to explain the observed transitions, a complementary inverse rainfall analysis was performed. For each accumulation window, all rolling precipitation totals exceeding the 90th percentile of the long-term distribution were identified, regardless of whether a documented lake transition occurred. The timing of these extreme rainfall periods was subsequently compared with the chronology of documented lake state transitions to assess how frequently anomalously wet conditions occurred without an associated geomorphic response. To assess whether the observed association between antecedent precipitation and lake state transitions differed from the seasonal climatic background, a seasonally constrained Monte Carlo randomization test was performed. For each documented formation and drainage event, random non-event dates were sampled from within ± 30 calendar days of the respective event's day of year, while dates within ± 30 days of any documented transition were excluded. This procedure was repeated 100,000 times separately for formation and drainage events. For each realization, the number of dates exceeding the 75th percentile in the 3-, 7-, 14-, and 30-day precipitation windows, as well as in at least one of these windows, was compared with the observed number of exceedances. Empirical one-sided p -values were calculated as the proportion of random realizations producing an equal or greater number of exceedances than observed. As a sensitivity test, random dates were additionally restricted to periods with the corresponding lake state (lake absent for formation and lake present for drainage) to ensure that control dates represented periods during which the respective transition was physically possible.

Potential seismic influences were investigated by comparing the chronology of documented lake state transitions with entries from the USGS earthquake catalog [30] covering the study period. Regional earthquakes with moment magnitudes (M_w) ≥ 5.0 were included in the temporal analysis to evaluate whether major seismic events coincided with repeated landslide-dam formation or drainage. In addition, an exploratory assessment was conducted for earthquakes with magnitudes between M_w 4.0 and 5.0 occurring within 30 km of the study site to identify potentially relevant local seismic events. Earthquake occurrence was subsequently compared with the documented chronology of lake transitions to evaluate whether recurrent landslide-dam evolution exhibited a systematic temporal relationship with seismic activity.

3. Results

3.1. Chronology of River Damming

The chronology of the Lacul fără nume landslide dam can be divided into a historic reconstruction phase and a modern monitoring phase. Consequently, the early evolution of the landslide dam prior to 1999 is characterized by substantial data gaps. However, despite the limited information, at least one lake state transition event could be reconstructed in 1983 based on the HEXAGON KH-9 imagery (Figure 4d). Figure 4c also shows that in 1980, the lake was clearly dammed, confirming the landslide-damming noted on the 1978 topographic map (Figure 4b). With the launch of the Landsat-7 mission in 1999, a much more continuous monitoring of the damming–breaching cycles was enabled, leading to a more robust dataset. With this data, a total of three recurrent cycles could be identified in the period between 1999 and 2014 (Figure 5). Between 2015 and 2026, another four cycles were observed (Figure 6). The satellite imagery collected during this study empirically confirms a minimum of eight events showing repeated lake formation and subsequent

drainage of the Lacul fără nume landslide dam. Details of the imagery used to detect lake state transitions are listed in Table 2.

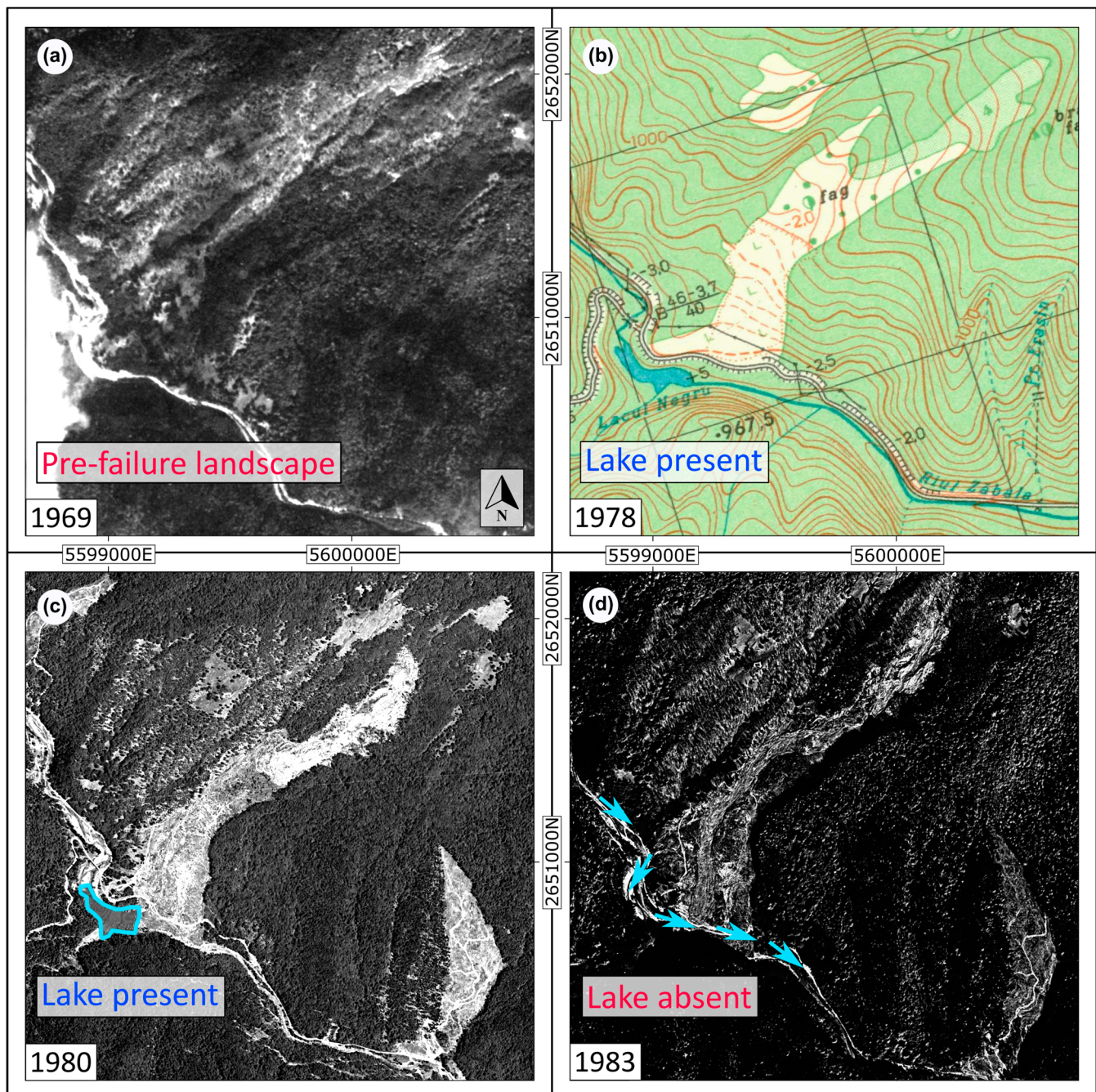


Figure 4. Historical reconstruction of landslide dam evolution between 1969 and 1983. (a) The pre-failure landscape. (b) A topographic map with the marked landslide and lake from 1978. (c) A landslide dam with an impounded lake in 1980. (d) A breached landslide dam in 1983. Data: (a) Declassified CORONA KH-4B imagery obtained from the USGS EarthExplorer archive; (b) Romanian Topographic Directorate (Direcția Topografică Română); (c,d) Declassified HEXAGON KH-9 imagery obtained through USGS EarthExplorer. Projection: EPSG: 3035.

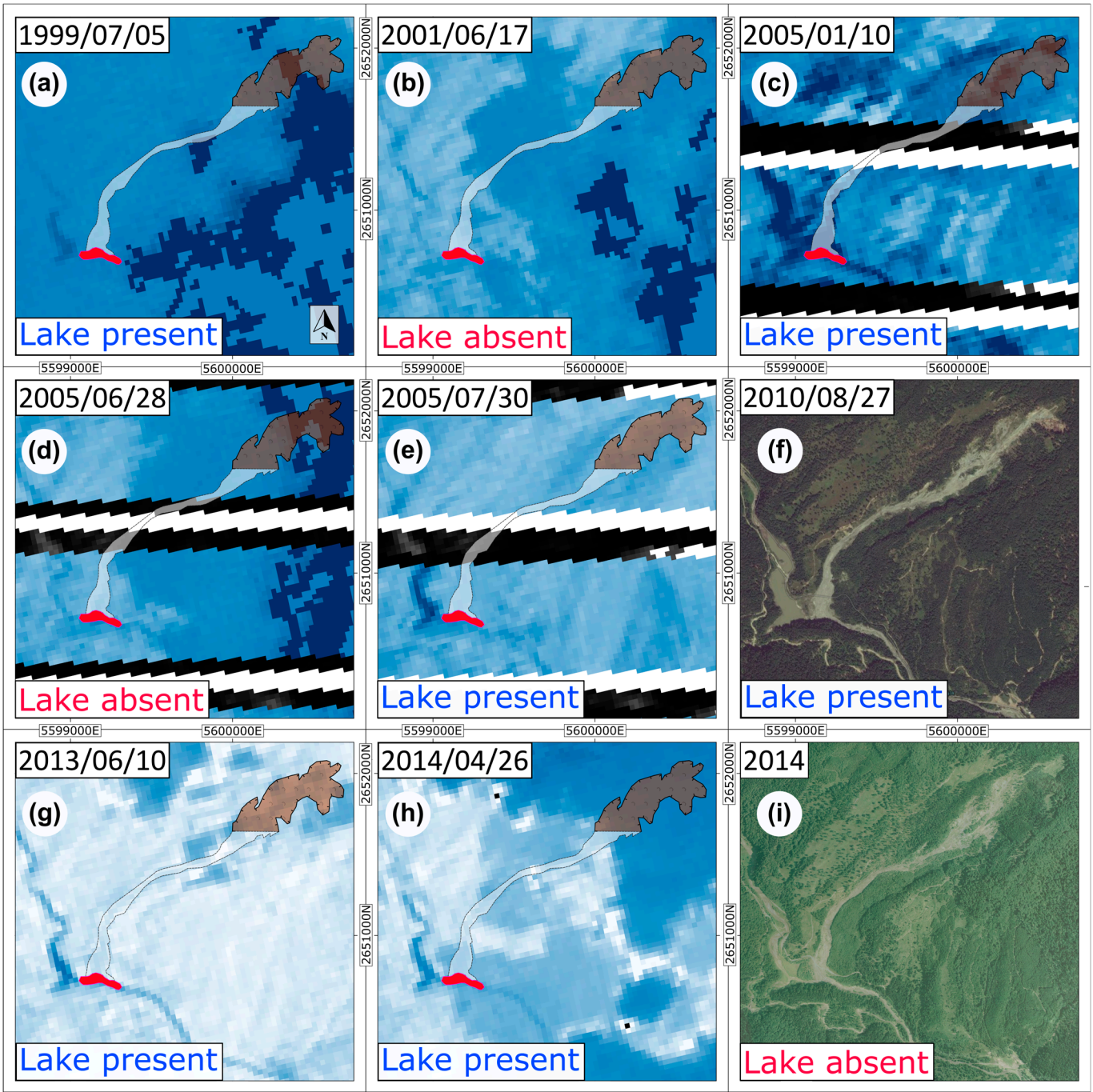


Figure 5. Key images from the data series of the early monitoring phase (1999–2014) with alternating phases of landslide-damming and breaching. The horizontal stripes of missing data in insets c–e are due to a sensor failure of the Landsat 7 satellite. Data: **(a–e)** Landsat 7 ETM+ (USGS EarthExplorer); **(f)** ESRI World Imagery Wayback (DigitalGlobe WV02); **(g,h)** Landsat 8 OLI/TIRS (USGS EarthExplorer); **(i)** Orthorectified Aerial Images–2014–2017 Edition (Romanian National Agency for Cadastre and Land Registration (ANCPI)). Projection: EPSG: 3035.

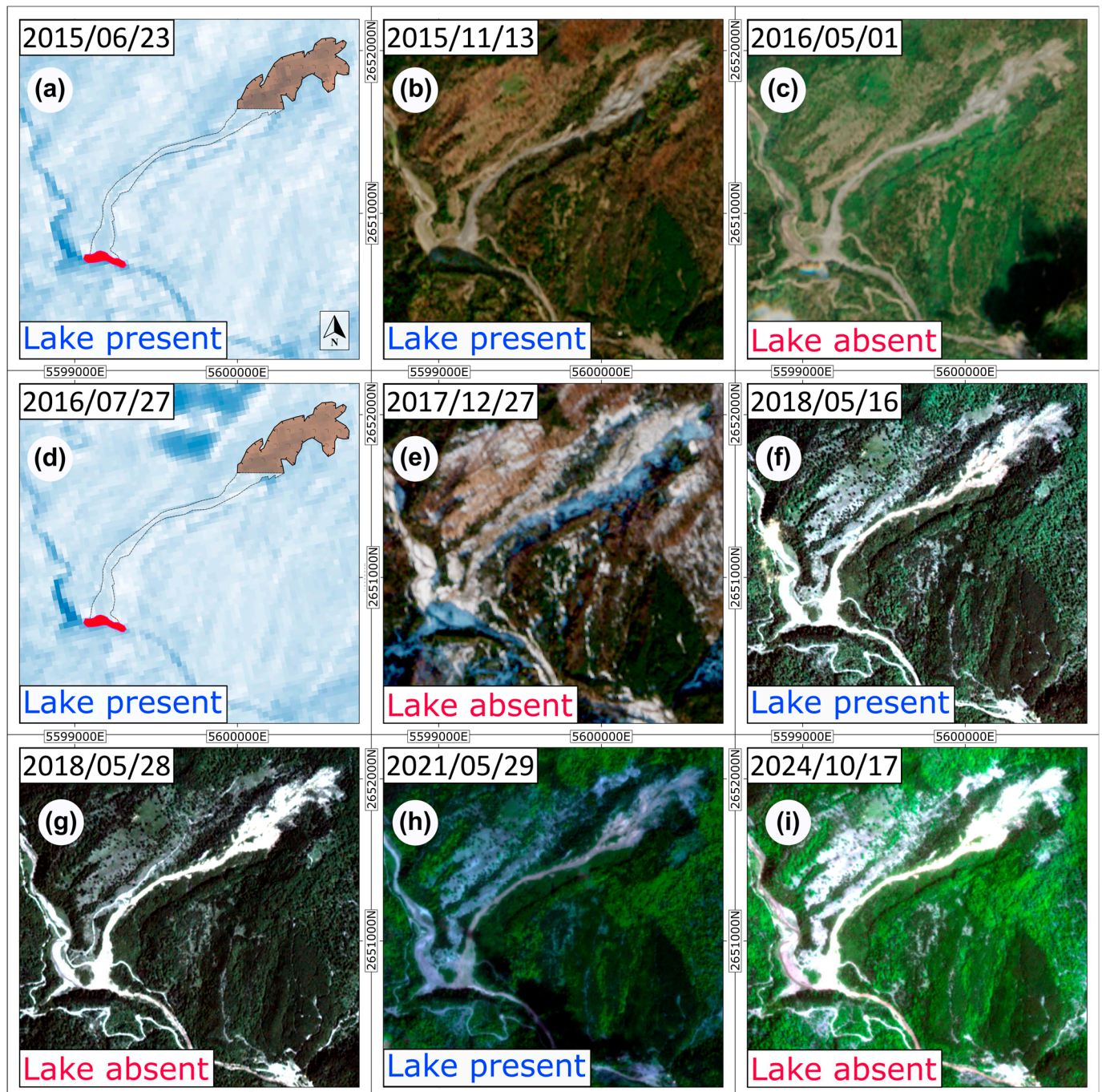


Figure 6. Key images from the data series of the late monitoring phase (2015–2026) with alternating phases of landslide damming and breaching. Data: (a,d) Landsat 8 OLI/TIRS (USGS EarthExplorer); (b,c,e–i) Planet Labs PBC, 2026. PlanetScope imagery. Projection: EPSG: 3035.

3.2. Breaching Cycles, Precipitation Events and Seismicity

The combined analysis of lake state transitions and antecedent precipitation indicates that the drainage phases of the Lacul fără nume landslide dam are frequently associated with elevated antecedent precipitation conditions, particularly over the 7- and 14-day windows. Excluding events with uncertain timing, seven lake-drainage phases were identified, of which five (71%) are associated with at least one antecedent precipitation window above the 50th percentile. When considering only high to extreme antecedent precipitation conditions (>75th percentile), four of the seven drainage phases (57%) exceed this threshold. The most pronounced case is the drainage phase of 28 June 2005, during which the 98.4th

(7-day), 97.7th (14-day), and 96.9th percentile (30-day) antecedent precipitation conditions were reached (Figure 7, Table 3). A similarly pronounced event is represented by the drainage phase of 17 June 2001, which also coincided with high antecedent precipitation values. In contrast, several drainage phases occurred during normal or only moderately elevated antecedent precipitation conditions. Examples include the drainage phases of 1 May 2016 and 28 May 2018, both of which are characterized by predominantly normal antecedent precipitation values across most investigated temporal windows.

Table 2. Data series of images used for the detection of lake state transitions.

Acquisiton Date	Lake Status	Image Source	Resolution (m)	Data Quality	MNDWI Applied
7 May 1999	Present	Landsat 7	30 (15)	Medium	Yes
17 June 2001	Absent	Landsat 7	30 (15)	Medium	Yes
10 January 2005	Present	Landsat 7	30 (15)	Low	Yes
28 June 2005	Absent	Landsat 7	30 (15)	Low	Yes
30 July 2005	Present	Landsat 7	30 (15)	Low	Yes
1 August 2014	Absent	Orthorectified Aerial Image *	unknown	High	No
23 June 2015	Present	Landsat 8	30 (15)	Medium	Yes
1 May 2016	Absent	Sentinel 2	10	High	No
27 July 2016	Present	Landsat 8	30 (15)	Medium	Yes
27 December 2017	Absent	PlanetScope Dove	~5-3	Very high	No
16 May 2018	Present	PlanetScope Dove	~5-3	Very high	No
28 May 2018	Absent	PlanetScope Dove	~5-3	Very high	No
29 May 2021	Present	PlanetScope Dove	~5-3	Very high	No
17 October 2024	Absent	PlanetScope Dove	~5-3	Very high	No

* Provided by the Romanian National Agency for Cadastre and Land Registration (ANCPI).

Table 3. Antecedent precipitation for landslide-dam events calculated over 3-, 7-, 14- and 30-day windows in mm. Percentiles refer to the empirical distribution of all corresponding rolling windows in the full precipitation time series. Classification ranges from normal (<50th percentile) to extreme (>95th percentile). Note: N = normal (<50th percentile), M = moderate (50–75%), H = high (75–90%), VH = very high (90–95%), E = extreme (>95%).

Date	Status	3 d	%	Class	7 d	%	Class	14 d	%	Class	30 d	%	Class
5 July 1999	Present	7.81	74.5	M	24.37	80.4	H	124.82	98.4	E	211.70	98.5	E
17 June 2001	Absent	25.90	94.8	VH	34.47	89.0	H	81.08	94.1	VH	134.31	91.1	VH
10 January 2005	Present	0.00	0.0	N	9.65	52.5	M	13.52	33.8	N	17.36	10.3	N
28 June 2005	Absent	7.61	73.9	M	75.41	98.4	E	110.93	97.7	E	183.57	96.9	E
30 July 2005	Present	0.00	0.0	N	12.02	59.3	M	22.09	51.7	M	218.12	98.8	E
1 August 2014	Absent	0.00	0.0	N	3.20	27.5	N	41.80	76.7	H	114.50	86.2	H
23 June 2015	Present	10.80	81.4	H	21.40	76.8	H	39.30	74.3	M	87.00	76.5	H
1 May 2016	Absent	0.00	0.0	N	2.80	25.5	N	31.70	66.0	M	110.00	85.2	H
27 July 2016	Present	0.10	27.6	N	0.20	10.4	N	0.20	2.2	N	37.10	35.2	N
27 December 2017	Absent	1.30	43.6	N	6.40	41.4	N	12.90	32.4	N	45.90	45.8	N
16 May 2018	Present	8.70	77.0	H	11.30	57.2	M	21.70	51.0	M	21.80	15.4	N
28 May 2018	Absent	0.00	0.0	N	0.00	0.0	N	13.50	33.7	N	33.70	30.7	N
29 May 2021	Present	13.70	85.7	H	21.00	76.3	H	37.90	73.0	M	45.50	45.3	N
17 October 2024	Absent	2.50	52.1	M	2.50	24.2	N	7.80	19.4	N	57.00	56.7	M

Of the seven documented lake-present phases, six (86%) are associated with at least one antecedent precipitation window above the 50th percentile, while five events (71%) exceed the 75th percentile in at least one investigated window. Several lake-present phases coincide with high or extreme antecedent precipitation conditions, such as the 5 July 1999 event, which reached the 98.4th and 98.5th percentiles for the 14- and 30-day windows, respectively. However, other lake-present phases occurred during normal or very low

antecedent precipitation conditions. Particularly noteworthy is the lake-present phase of 27 July 2016, which is associated with near-zero antecedent precipitation across most investigated windows. All investigated events and associated antecedent precipitation values for the different temporal windows are summarized in Table 3.

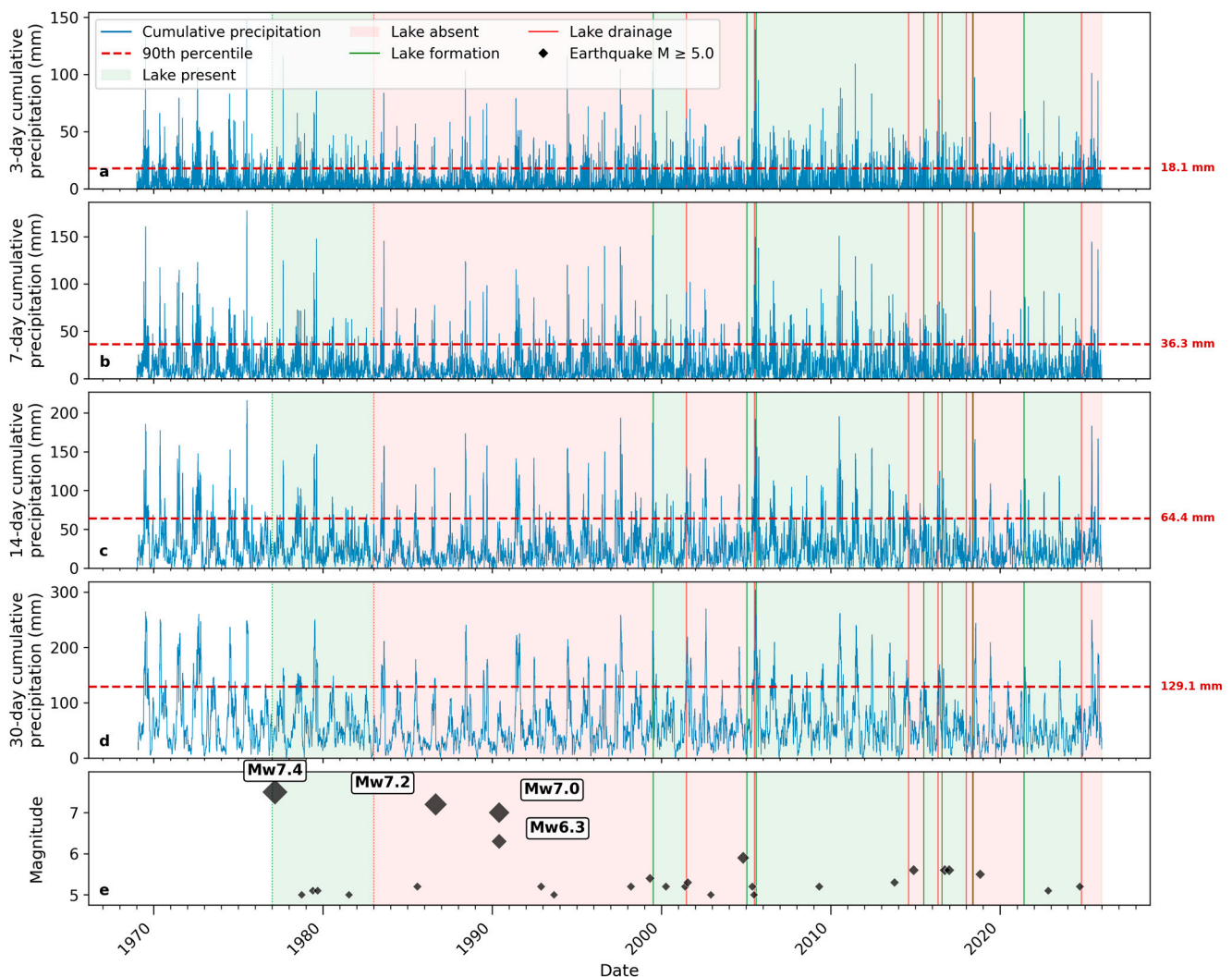


Figure 7. Cumulative precipitation data from Lăcăuți meteorological station and major seismic events overlain with phases of lake presence and absence. Panels (a–d) show the investigated windows with the 90th percentile value highlighted. Panel (e) shows the occurrence of major earthquakes.

However, the results of the inverse rainfall analysis show that heavy rainfall was frequent without documented dam formation or drainage. In total, 276 episodes were identified in which at least one of the calculated window totals exceeded the 90th percentile, of which only three directly overlapped a transition during the 1999–2024 chronology. This pattern is consistent across all four accumulation windows (Figure 7a–d). In addition, the seasonally constrained Monte Carlo randomization test showed that the observed occurrence of high antecedent precipitation at lake state transitions did not differ significantly from the seasonal climatic background. Five of seven formation events (71.4%) exceeded the 75th percentile in at least one of the four precipitation windows, compared with a mean of 66.4% for seasonally matched random non-event dates ($p = 0.574$). For drainage events, four of seven events (57%) exceeded the 75th percentile in at least one window, compared with 58.4% for random dates ($p = 0.700$). None of the individual 3-, 7-, 14-, or 30-day precipitation windows showed a significant positive association with formation or

drainage events (all $p > 0.05$). The lowest p -value was obtained for the 30-day precipitation preceding drainage events (four of seven events; $p = 0.234$). Restricting random dates to periods with the corresponding lake state produced comparable results, with no significant association for either formation ($p = 0.478$) or drainage events ($p = 0.663$). Figure 7e shows that during the study interval, 28 earthquakes with $M_w \geq 5.0$ occurred. Although the initial formation of the landslide dam in 1977 coincided with the exceptional M_w 7.4 Vrancea earthquake, subsequent lake state transition events show no systematic association with regional seismic activity.

4. Discussion

4.1. Recurrent Formation and Drainage Dynamics

The results of this study demonstrate that the Lacul fără nume landslide dam can be classified as a dynamic system, which is characterized by frequent reactivations, rather than a stable geomorphic structure. Remote sensing analyses show alternating phases of landslide dam formation and impoundment, lake persistence, and breaching and drainage. Based on the reconstruction of eight such cycles, it is likely that the Lacul fără nume landslide dam represents a feedback system, which after breaching experiences a partial remobilization of the unstable landslide mass in the source area (Figure 1). This study assumes that the temporary stable dam breaches either due to overtopping, internal erosion, siltation or anthropogenic interference causing the drainage of the lake. Based on field observation, the residual dam material persists in the landscape until it gets overprinted by debris flow material mobilized during a subsequent slope failure, causing a re-blockage of the river channel and eventually the renewed impoundment of a lake. During these cycles, the extent and observed persistence times of the lake are highly variable (Table 4, Figure 8). Only considering the timespans of the more constant monitoring phase between 1999 and 2026, the shortest minimum persistence time is 12 days, while between 2005 and 2014, the lake was stable for more than 9 years. Taken together, the post-1999 median duration of the lake is approximately 1.4 years (518 days). However, it must be noted that prior to 1999, there is a substantial data gap spanning over a period of 30 years. During this phase, only three data points exist that allows the reconstruction of one single recurrent cycle. Given the median of 1.4 years for the period between 1999 and 2026, it is conclusive that the frequency of recurrent cycles between 1969 and 1999 is massively underrepresented. Since the monitoring of the modern period shows that under favorable conditions, the lake can remain stable for almost a decade (e.g., 2005–2014), it is not possible to reliably assume the number of cycles that might have happened in the historical phase between 1969 and 1999.

Table 4. Observed longevity and maximum surface area extent of lake phases during the monitoring phase (1999–2026).

Lake Present	Lake Drained	Minimum Observed Persistence	Maximum Observed Lake Extent
5 July 1999	17 June 2001	713 days	31,280 m ²
10 January 2005	28 June 2005	169 days	82,610 m ²
30 July 2005	1 August 2014	3289 days	59,970 m ²
23 June 2015	1 May 2016	313 days	29,300 m ²
27 July 2016	27 December 2017	518 days	27,760 m ²
16 May 2018	28 May 2018	12 days	33,620 m ²
29 May 2021	17 October 2024	1237 days	31,540 m ²

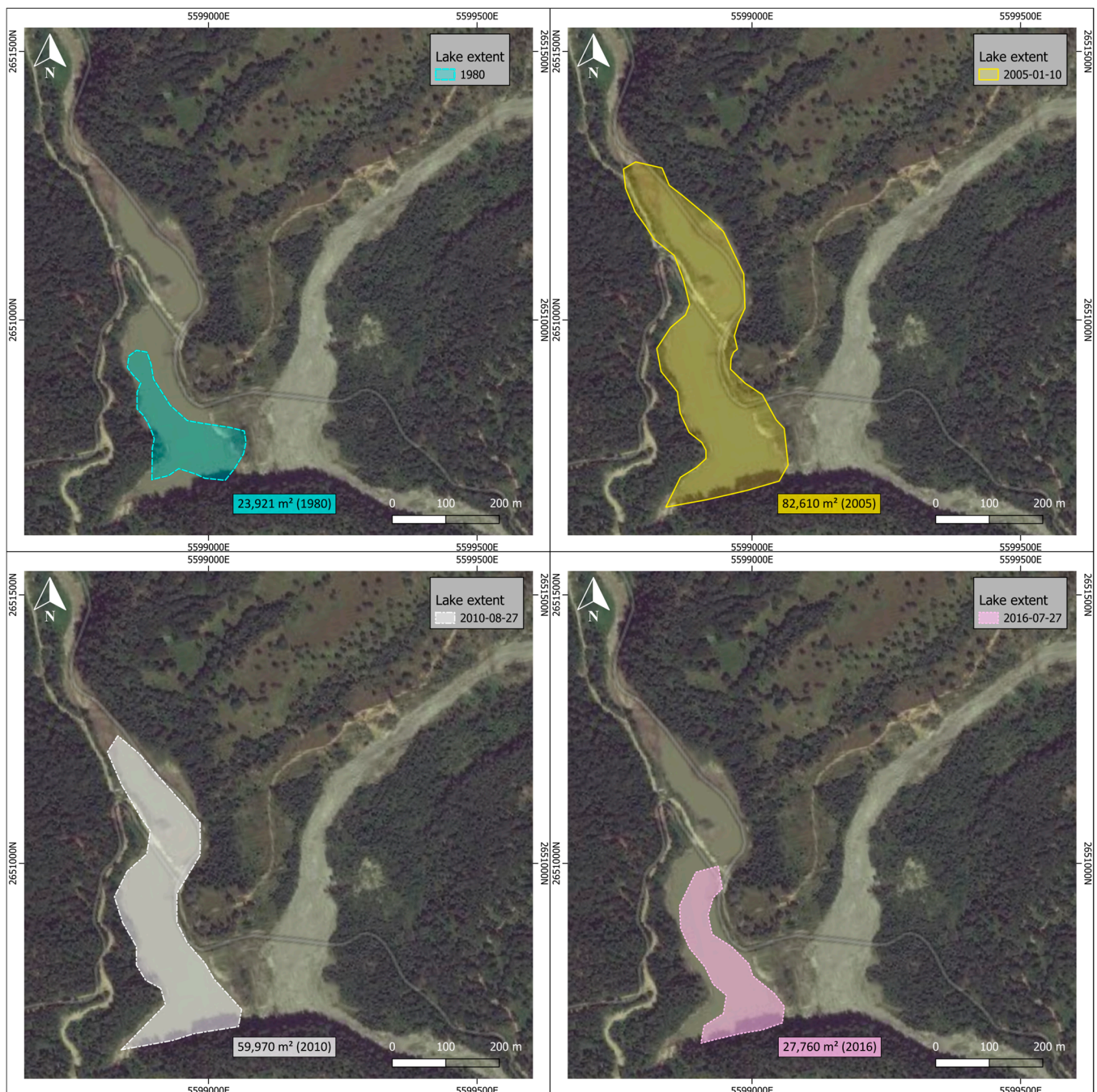


Figure 8. Minimum, maximum and intermediate lake extent of Lacul fără nume. Data: ESRI World Imagery Wayback (DigitalGlobe WV02) (Basemap). Projection: EPSG: 3035.

4.2. Role of Precipitation Conditions and Seismicity

The antecedent precipitation within cumulative time windows in the area was compared to the occurrence of recurrent cycles because the triggering of debris flows is commonly associated with the intensity and duration of rainfall events [31–33]. As stated in the Section 3, the transitional events are frequently associated with elevated antecedent precipitation, with at least one observed window above the 50th percentile. However, because the 50th percentile merely separates above-average from below-average conditions, subsequent analyses focus primarily on antecedent precipitation windows exceeding the 75th percentile, representing distinctly elevated hydrological conditions. While slightly elevated antecedent precipitation (>50th percentile) is common, in both classes, high to

extreme precipitations (>75th percentile) are more frequent during lake-present phases (71%) than lake-drained phases (57%). Nonetheless, while not allowing an unambiguous identification of the trigger mechanism, the correlation between high to extreme antecedent precipitations and lake-present phases indicates an association between dam formation and high-magnitude rainfall events. Periods of high antecedent precipitation may contribute to slope instability and downslope material mobilization, which eventually leads to a renewed blockage of the valley floor. However, the lake present phase from 27 July 2016 with near-zero values across most investigated windows represents an outlier, demonstrating that intense periods of rainfall alone cannot explain the recurrent formation of the landslide dam.

The multifactorial controls on the evolution of the Lacul fără nume landslide dam become particularly apparent when considering the drainage phases. Four of the seven documented drainage events were associated with high to extreme antecedent precipitation, suggesting a less consistent hydrological association than for dam formation. Some intense precipitation events may have raised the lake level sufficiently to promote failure through overtopping or internal erosion, whereas drainage under low precipitation conditions indicates that additional controls must be involved. This interpretation is supported by both the inverse rainfall test and the seasonally constrained Monte Carlo analysis. Numerous precipitation events exceeding the 90th percentile occurred without an observable lake-state transition, while the frequency of high antecedent precipitation associated with documented transitions did not differ significantly from the seasonal climatic background. Rainfall alone therefore cannot explain the recurrent damming and drainage but may act as a contributing or preconditioning factor whose influence depends on the evolving hydraulic and geomorphic state of the system. Given the small number of documented transitions, the absence of a statistically significant association does not exclude an influence of precipitation. The comparison with regional seismicity similarly revealed no systematic association with recurrent lake-state transitions. Most documented transitions were not preceded by a major earthquake within the investigated time windows, while several major earthquakes occurred without detectable changes in lake state. Anthropogenic intervention provides an additional source of complexity, particularly for interpreting drainage events. During the field visit, two local residents and five forest workers consistently reported that the dam had been artificially breached on at least one occasion using heavy machinery to reduce the risk of uncontrolled flooding. Although the timing and frequency of such interventions could not be reconstructed from the analyzed imagery, artificial breaching provides a plausible explanation for at least some drainage events occurring under low or near-zero precipitation and in the absence of notable seismic activity. At the same time, the unknown timing of these interventions limits the extent to which individual drainage events can be attributed to natural hydrological or seismic forcing. Taken together, the findings indicate that the major 1977 Mw 7.4 Vrancea earthquake [34] may likely have played an important role in initiating the landslide dam system, but the recurrent evolution during the following decades was governed primarily by hydrometeorological forcing rather than repeated seismic triggering. However, the repeated evolution of the Lacul fără nume landslide dam cannot be explained by a single triggering mechanism and is best described by the interaction of external forcing, primarily antecedent precipitation, with time-dependent geomorphic and hydraulic controls that determine whether the system responds to a given rainfall event. In addition, anthropogenic influences may also play a role in slope reactivation. These include extensive deforestation in the Upper Zăbala basin, as reported by Istrate et al. (2023) [35], as well as associated road cutting at the foot of the slope. The quantification of the anthropogenic effects on the slope stability requires a multi-temporal land cover use analysis which is beyond the scope of this study.

4.3. Uncertainties and Limitations

The datasets presented in Table 1 range in resolution from 3 m to 30 m, thereby introducing a spatial resolution problem. It must be noted that imagery acquired prior to Landsat 7 lacks sufficient spatial resolution and image quality to reliably distinguish between impoundment and river channels. Even the Landsat 7–8 imagery only allows a separation between lake state transitions when the lake area is big enough to match or exceed the sensors' effective resolution. In consequence, small-scale lake formation events, where the surface extent of the landslide-dammed lake is smaller than the sensors' resolution, could be interpreted as non-damming phases. Conclusively, the reported cycles of lake presence and absence represent a minimum rather than a complete event inventory. Further complication arises from extensive cloud coverage or data gaps due to sensor failures, as is the case with Landsat 7 data exceeding June 2003. Another limitation arises from the temporal availability of the satellite imagery used to reconstruct the lake chronology. While PlanetScope provides near-daily imagery of the study site, Landsat 7 and Landsat 8 each have a nominal revisit period of 16 days. Therefore, the chronology established in this study can only record the earliest available date of lake formation or drainage and not the exact timing of dam formation or respectively breaching.

Further uncertainty arises from the approximately 20 km distance between the study site and the Lăcăuți meteorological station. Although precipitation recorded at Lăcăuți is assumed to provide a reasonable approximation of conditions at the study site, local variations in precipitation between the respective valleys cannot be excluded. Nevertheless, the Lăcăuți record represents the only comprehensive precipitation dataset available in close proximity to the study area that covers the complete chronology of nearly five decades. The assessment of seismic influences is also subject to uncertainty, as earthquake magnitude and epicentral distance provide only first-order indicators of ground shaking at the study site. Focal depth, attenuation, and local geological conditions may substantially affect the actual shaking intensity, particularly given the intermediate-depth seismicity of the Vrancea region. A site-specific ground-motion analysis would be required to quantify these effects but is beyond the scope of this study.

4.4. Implications for Downstream Hazards

Since the Lacul fără nume landslide dam is located in a remote area, it currently poses only a minor risk to human infrastructure, such as nearby roads that are primarily used by forest workers to transport tree trunks, and a mountain cabin located 1.5 km downstream of the site. The closest settlement that could be affected by downstream flooding is the village of Brădăcești situated approximately 13 km downstream. Although the potential hazards associated with the Lacul fără nume landslide dam are relatively small, the site demonstrates that debris-flow-generated landslide dams can evolve into persistent geomorphic hazards capable of remaining active within the landscape for multiple decades. However, remotely sensed or data-driven spatial outputs used to characterize such systems should not be interpreted as direct hazard or risk assessments without explicitly considering process constraints, event frequency, independent validation, and associated uncertainties [36,37].

5. Conclusions and Outlook

The present study confirms the Lacul fără nume landslide dam as a dynamic system characterized by frequent damming–breaching cycles that occurred at least eight times within the last 49 years. Among the recurrent landslide dams reported in the literature, the Lacul fără nume landslide dam represents a particularly well-documented example, with multiple reactivations occurring over timescales ranging from months to decades.

Given the limited documentation of recurrent landslide dams in the scientific literature, this study provides a valuable long-term record of lake state transitions as proxies for repeated damming and breaching cycles within such systems. Furthermore, the results demonstrate that the mechanisms controlling repeated dam formation and breaching are complex and cannot be attributed solely to elevated precipitation or the occurrence of major earthquakes.

Overall, this study provides a conceptual model of landslide dams as dynamic geomorphic systems based on the reconstruction of a field case characterized by frequent damming–breaching cycles leading to lake state transitions, thereby establishing a framework for future investigations aimed at improving the understanding of the still poorly constrained mechanisms governing recurrent landslide damming. While remote sensing and field investigations have already provided valuable insights, future studies should incorporate long-term in situ monitoring of both the landslide dam and its source area to further improve the understanding of such systems.

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