

Human-enhanced tsunami hazard in large lakes

Received: 8 January 2026

Accepted: 21 September 2026

Published online: 15 October 2026

 Check for updates

Muhammad Naveed Zafar^{1,2}✉, Pierre Sabatier¹, Denys Dutykh³, William Rapuc^{1,4}, Raphaël Paris⁵, Andrea Piccin⁶, Pascal Vuillemin⁷ & Flavio S. Anselmetti⁸

Worldwide, human-induced erosion enhances sediment delivery to lake deltas, increasing their susceptibility to collapse. In Lake Iseo, northern Italy, two millennia of intensified land use tripled sediment flux, oversteepening the delta and preconditioning it for failure. Here we show from geological records and numerical simulations that earthquakes in 1117 CE (Mw 6.5) and 1222 CE (Mw 6.0) triggered major subaqueous delta collapses, generating massive tsunamis with maximum run-ups of ~50 m and ~13 m, respectively. Historical accounts from the Vatican Library and archeological evidence support these reconstructions. Since the last collapse, eight centuries of human-induced erosion have rebuilt the delta, leaving shoreline populations highly vulnerable to future earthquake-triggered failures. A global lake synthesis showed that human-driven erosion has reached its highest levels since the Industrial Era, progressively overloading deltas worldwide; thus, similar catastrophic failures may become more likely in the future. These findings reveal a persistent, human-amplified mechanism of lacustrine tsunami generation and intensity with major implications for hazard assessment.

Worldwide, land use has drastically accelerated erosion^{1–4}, resulting in increased sediment yield and accelerated delta progradation in downstream lakes^{5–7}, which are especially vulnerable because of their steeper slopes, confined basins, and smaller spatial extents. Paleoenvironmental records show that since the Holocene, human activities such as agriculture, pastoralism, urban expansion, deforestation, and burning have been the main drivers of amplified soil erosion globally^{8–15}, increasing sediment fluxes to deltas by up to 100-fold in some regions¹⁶. These abrupt and extensive sediment inputs have profoundly reshaped delta morphologies⁵, overloaded subaquatic slopes, and weakened structural stability,

making deltas more prone to collapse under seismic and gravitational stress^{17,18}.

Driven by intensified land use, multiple lacustrine delta collapses have been documented globally^{17,19–28}. However, the role of anthropogenic sedimentation in tsunami hazards remains critically understudied, especially in tectonically active regions, where sustained sediment loading destabilizes deltaic slopes, preconditioning them for catastrophic failure during seismic events that could generate large tsunamis^{24,29–31}.

In this work, we examine the tsunamigenic consequences of long-term human-driven sediment accumulation in Lake Iseo (60.9 km²),

¹Environnements, Dynamiques et Territoires de la Montagne (EDYTEM), Université Savoie Mont Blanc, Centre National de la Recherche Scientifique (CNRS), Le Bourget-du-Lac, France. ²Laboratoire de Mathématiques (LAMA), Université Grenoble Alpes, Université Savoie Mont Blanc, Centre National de la Recherche Scientifique (CNRS), Chambéry, France. ³Mathematics Department, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates.

⁴Department of Earth Sciences, Durham University, Durham, UK. ⁵Université Clermont Auvergne, Centre National de la Recherche Scientifique (CNRS), Institut de Recherche pour le Développement (IRD), Observatoire de Physique du Globe de Clermont-Ferrand (OPGC), Laboratoire Magmas et Volcans (LMV), Clermont-Ferrand, France. ⁶Regione Lombardia, Direzione Generale Territorio e Sistemi Verdi, Milan, Italy. ⁷Langages, Littératures, Sociétés. Études Transfrontalières et Internationales (LLSETI), Université Savoie Mont Blanc, Chambéry, France. ⁸Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Baltzerstrasse 1+3, Bern, Switzerland. ✉e-mail: muhammad.zafar.naveed@gmail.com

one of the largest lakes in northern Italy. By integrating geophysical, sedimentological, historical, and archeological data with advanced numerical modeling, we reconstruct two medieval delta collapses and assess their tsunamigenic potential. This multidisciplinary investigation highlights how sustained anthropogenic pressure can lead to repeated delta collapses, which are capable of generating devastating tsunamis over relatively short timescales. Our findings underscore the urgent need to incorporate human-driven sediment dynamics into tsunami hazard assessments in densely inhabited lacustrine environments, particularly those in tectonically active regions.

Results

The human footprint on Lake Iseo's Delta

Lake Iseo (Italy) is located at the downstream end of Val Camonica (Fig. 1), one of the largest valleys of the southern European Alps. The Lake Iseo catchment (1777 km²) is characterized by steep topography and is drained by the Oglio River (Fig. 1), which inflows the lake from the north, supplying substantial sediment that forms a large delta. Extensive human activity in the catchment is well documented by archeological, historical, palynological, and paleoenvironmental studies^{32–37}. Since the Roman period, intensified deforestation, agriculture, and pastoralism have significantly increased hillslope erosion, resulting in a threefold rise in sediment flux to the lake compared with earlier Holocene background levels³². This abrupt human-driven erosion rapidly built up and steepened the Oglio River Delta at the lake's

northern margin, overloading subaqueous slopes and increasing their susceptibility to collapse during seismic shaking¹⁷.

The Val Camonica region has experienced moderate to high seismic activity due to the complex collisional and postcollisional phases of the Alpine orogeny³⁸. Several destructive earthquakes have been recorded over the last two millennia³⁹. Notably, two major medieval earthquakes, the 1117 CE Verona earthquake (Mw 6.5)^{39,40} and the 1222 CE Brescia earthquake (Mw 6.0)^{39,41}, affected the Lake Iseo region, with estimated macroseismic intensities of approximately VI–VII⁴² and V–VI⁴³, respectively. They triggered massive subaqueous delta collapses in Lake Iseo¹⁷ and induced minor slope failure, likely along the escarpment between Monte Isola and the eastern shore⁴⁴. According to detailed sediment core and seismic reflection analyses, these delta collapses are recorded as the thickest mass-wasting deposits (MWDs, or megaturbidites) in the deep basin of Lake Iseo¹⁷. The 1117 CE earthquake produced an event deposit (MWD7 in Supplementary Fig. 1), which reached a maximum thickness of ~7 m and an estimated volume of $6.2 \times 10^7 \text{ m}^3$ derived from the interpolated thickness (Fig. 2c). This exceptional event is linked to approximately six centuries of human-driven sediment accumulation at the Oglio River Delta following the last delta collapse in the 6th century (Supplementary Fig. 3)¹⁷. After the collapse of the 1117 CE, continued sedimentation from ongoing human activity rebuilt and preconditioned the delta slopes for another collapse, which occurred approximately one

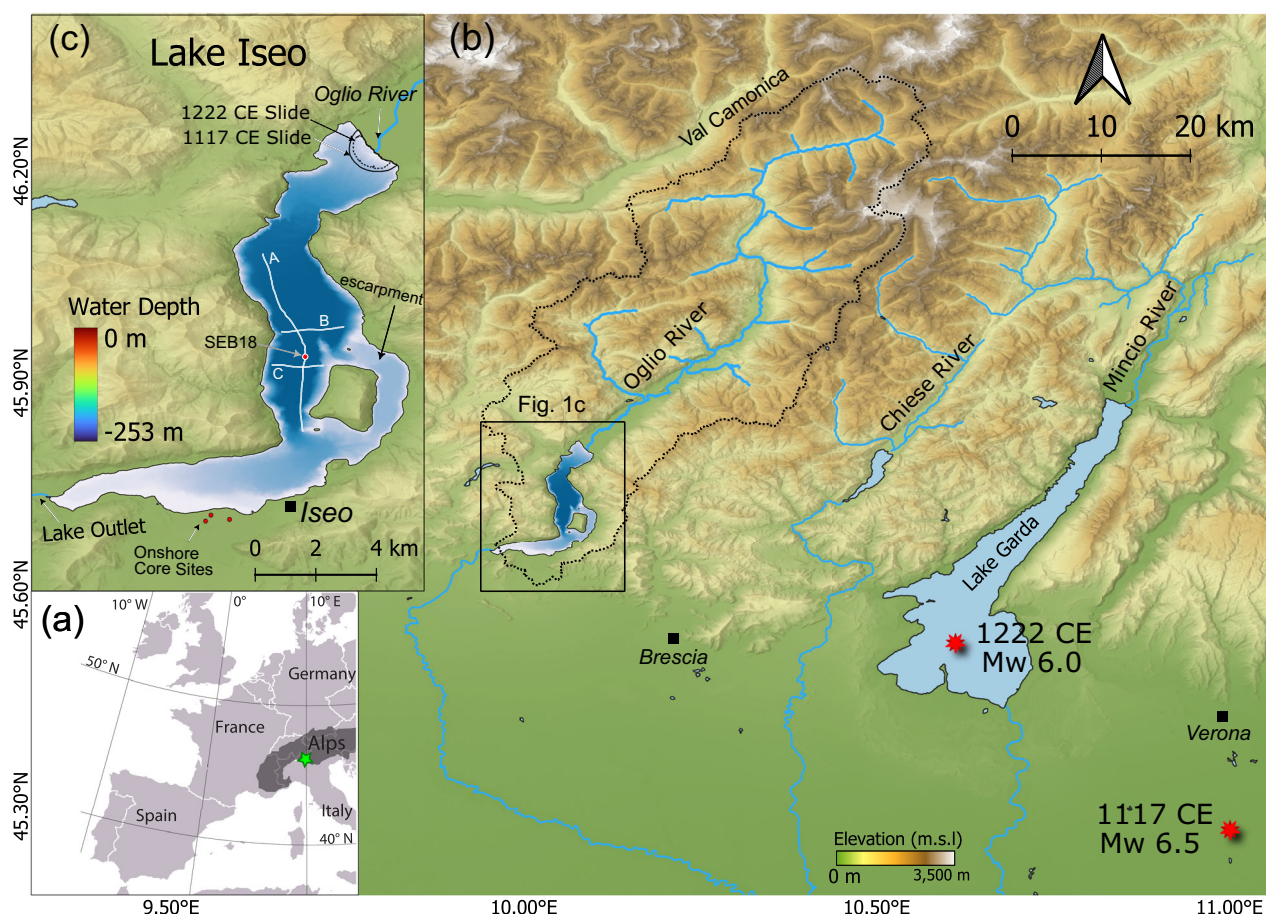


Fig. 1 | Location and geomorphological context of Lake Iseo. **a** Location of the study area in the central Southern Alps, northern Italy. **b** Topographic map showing the Val Camonica watershed (black dashed line), along with the extent of Lake Iseo and adjacent basins, the locations of the main cities, and the epicenters of the 1117 and 1222 CE earthquakes. **c** The detailed bathymetry of Lake Iseo, showing the

location of core SEB18 (core data in Supplementary Fig. 2), some of the seismic survey lines in white A–C (corresponding seismic profiles in Supplementary Fig. 1), the onshore core sites collected in this study, the Oglio River Delta, and the locations of the two medieval delta collapses.

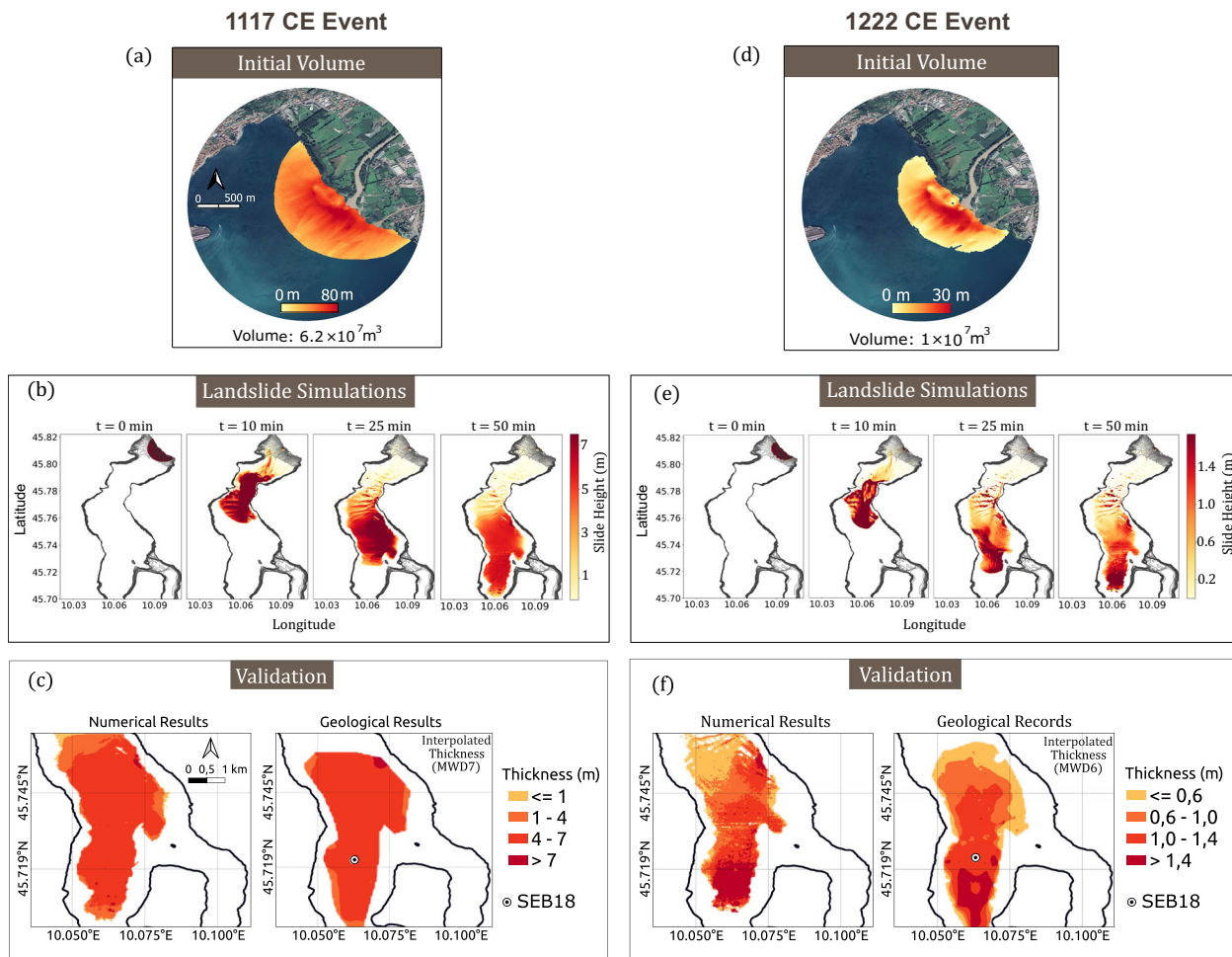


Fig. 2 | Landslide modeling and its validation with geological records for the 1117 CE and 1222 CE events. a, d Initial reconstructed landslide volumes. **b, e** Simulated landslide thickness evolution over time. **c, f** Comparisons between

modeled deposit thicknesses and those interpolated from seismic profiles are shown for the **a–c** 1117 CE event and **d–f** 1222 CE event. Background satellite imagery in (**a, d**): Google ©2026 CNES/Airbus, Maxar Technologies.

century later during the 1222 CE earthquake and produced a somewhat thinner layer (MWD6 in Supplementary Fig. 1) with a maximum thickness of ~2 m and a volume of $1 \times 10^7 \text{ m}^3$ (Fig. 2f). This rapid rebuilding is supported by a first-order estimate based on the mean deep-basin sedimentation rate ($\sim 3 \text{ mm yr}^{-1}$)¹⁷ over the $\sim 18 \text{ km}^2$ depositional area (below 210 m water depth), which indicates that $\sim 5.7 \text{ Mm}^3$ of sediment accumulated between the 1117 and 1222 CE events. Although it is lower than the $\sim 10 \text{ Mm}^3$ mobilized in 1222 CE, this estimate is conservative because it reflects fine-grained sediment preserved in the deep basin and does not include coarser sediment stored at the delta front, where the failure originated. The accommodation space created by the 1117 CE collapse likely further enhanced sediment trapping and rapid rebuilding of the unstable delta wedge. These two events illustrate how increases in sediment supply from human activities may amplify the likelihood of delta collapses in seismically active regions.

Reconstruction of catastrophic tsunami events

To assess the tsunami hazards associated with both medieval delta collapses, we reconstructed the landslides and resulting tsunamis by quantifying the event deposits and conducting high-resolution numerical modeling. The reconstruction was based on high-resolution LiDAR topographic and multibeam bathymetric datasets acquired in 2002 by Regione Lombardia and the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) within the Italian National Geological Mapping Program (CARG)^{45,46}. The present-day

high-resolution bathymetry was used as a geomorphological analogue for the pre-failure delta morphology because sustained sedimentation following the medieval failures largely infilled the delta front and obscured the original landslide scars. This was done assuming that continued sediment delivery after the medieval failures rebuilt the delta along a similar depositional pathway.

Based on this framework, the post-failure delta morphology was reconstructed in GIS by removing areas of sediment accumulation and restoring a plausible failure-scar morphology. This reconstruction was guided by large-scale bathymetric trends, erosional features, and the present-day morphology of the Oglio Delta front. Landslide source volumes were then estimated as the difference between the reconstructed post-failure surface and the modern bathymetric surface. The reconstruction was iteratively refined until the estimated source volumes matched the volumes of the mapped mass-wasting deposits identified from seismic reflection profiles and sediment-core data in the deep basin, yielding source volumes of $6.2 \times 10^7 \text{ m}^3$ for the 1117 CE event and $1.0 \times 10^7 \text{ m}^3$ for the 1222 CE event (Fig. 2a, d). We then simulated landslide dynamics using a viscoplastic rheological model assuming a single-event failure mechanism. This assumption is supported by the sedimentological structure of the deep-basin event deposits, which comprise an erosive sandy base interpreted as a high-energy remobilization phase, followed by a single upward-fining depositional episode without evidence for repeated grading or multiple stacked subevents¹⁷. This unit is overlain by thick homogeneous deposits interpreted as suspension settling associated with basin-wide

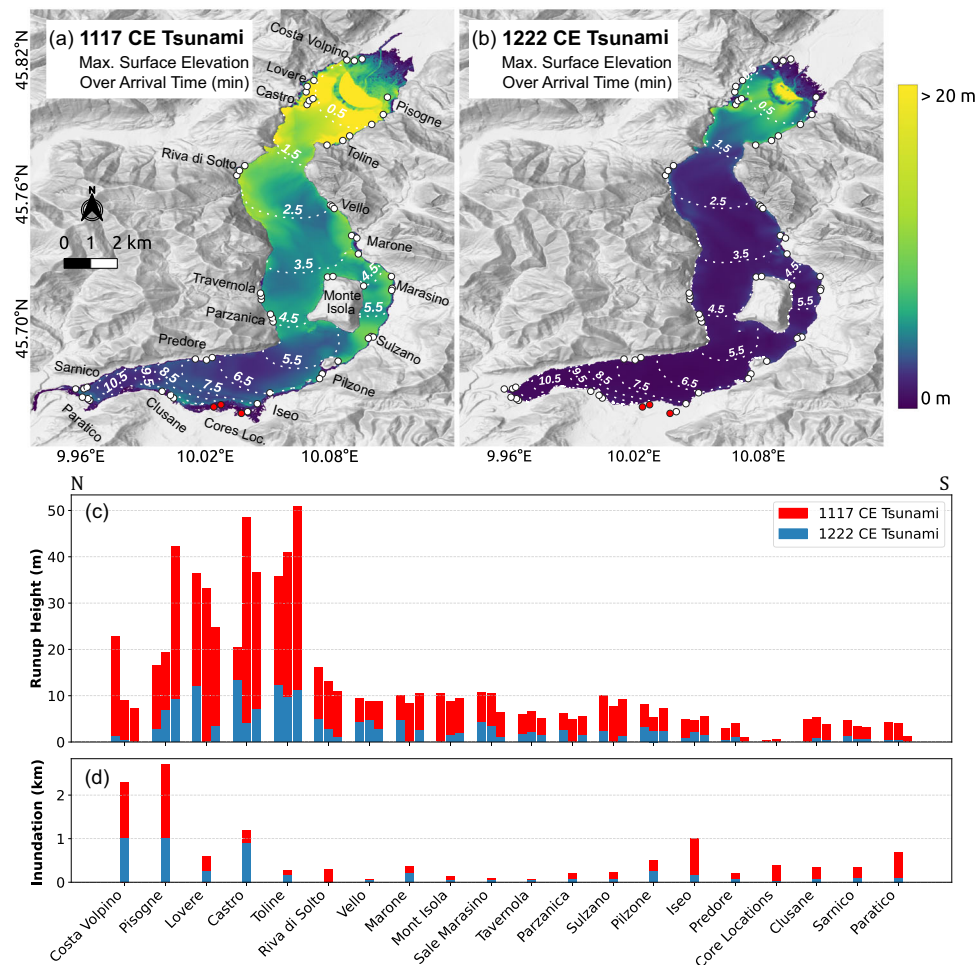


Fig. 3 | Tsunami modeling and its coastal impact for the 1117 CE and 1222 CE events. Maximum tsunami surface elevation (colorbar) and wave arrival times in minutes (contour lines) for the **a** 1117 CE and **b** 1222 CE events. White dots indicate the municipalities surrounding Lake Iseo, and red dots indicate the onshore core

sites collected in this study. **c** Run-up heights and **d** inundation distances at the sites marked in **(a)**, ordered from north to south (N–S), for the 1117 CE (red) and 1222 CE (blue) events.

seiche oscillations⁴⁷, with an upper fine-clay interval representing the final stage of suspension settling.

Details of the modeling approach and parameter selection are provided in the Methods section. The temporal evolution of landslide thickness, from initiation to final deposition in the deep basin, is shown in Fig. 2b, e. Both landslides originated at the Oglio Delta, but their final depositional geometries differ slightly. During the 1222 CE event, a greater portion of the mass propagated farther into the basin compared to the 1117 CE event, likely due to greater accommodation space, as the 1117 CE deposits had already filled the northeastern deep basin with substantial sediment a century earlier. Moreover, the 1222 CE landslide had relatively high water content and a large proportion of coarse sediment (Supplementary Fig. 2), resulting in a relatively low shear strength. This allowed the material to travel more rapidly (Fig. 2e), with most of the sediment reaching farther into the deep basin. The modeled deposit thicknesses and their spatial distributions strongly agree with those inferred from seismic profiles and sediment core data for both events (Fig. 2c, f), thus validating the rheological assumption and parameterization of our landslide modeling approach.

Following this validation, we simulate the resulting tsunamis based on time-dependent changes in water depth induced by landslide motion. We calculated tsunami wave propagation and inundation by using a nonlinear hydrodynamic model for both events at a 10 m spatial resolution. Details of the tsunami models, Froude number estimation, and sensitivity analyses of dispersion and landslide

initiation depth are provided in the Methods section. The maximum tsunami wave heights over the arrival times for both events, along with the corresponding run-up heights and inundation distances at the marked locations, are shown in Fig. 3. Our simulations reveal that the medieval delta collapses in Lake Iseo generated some of the largest subaquatic landslide-induced tsunamis ever inferred in a lacustrine setting. The 1117 CE event produced wave heights greater than 50 m in the northern part of the lake (Fig. 3a, c). This massive tsunami wave inundated nearby shores within just one minute and propagated up to ~2.7 km inland (Fig. 3d). The subsequent collapse in 1222 CE also generated a large tsunami (Fig. 3b), with waves peaking at ~13 m (Fig. 3c) and inundation extending up to ~1 km inland (Fig. 3d). Both tsunamis propagated rapidly across Lake Iseo and were strongly influenced by Monte Isola, the central island, which acts as a natural barrier, splitting the waves and partially shielding the cities behind it. Despite this protection, areas such as Iseo still experienced significant impacts, with maximum wave heights of ~5.5 m (1117 CE) and ~2 m (1222 CE), arriving ~7 min after the landslides (Fig. 3).

Historical and archeological tsunami evidence

Our numerical tsunami reconstructions are strongly supported by historical and archeological evidence. A vivid account from a 12th-century manuscript⁴⁸ preserved in the Vatican Library describes the catastrophic 1117 CE event, which states on folio 184r: “*Lacus quoque adeo excreverunt ut in villis iuxta positos habitantes paucissimi ab hoc*

periculo evaderent. Multa quoque castella et arces cum interitu habitantium miserabiliter diruerunt.” meaning, “The lake (Iseo) overflowed so much that very few of the inhabitants of the nearby villages escaped this danger. Many castles and fortresses also collapsed miserably, with the destruction of their inhabitants”. Detailed information on individual buildings is limited, making it difficult to validate the exact tsunami run-up and inundation. However, archeological evidence from the Pieve church of Sant’Andrea d’Iseo provides useful constraints⁴⁶. The church underwent major reconstruction shortly after the 1117 CE event, involving both its lower and upper parts. Whether this damage resulted from seismic shaking, tsunami impact, or both cannot be determined. Our simulations indicate that the 1117 CE tsunami reached the shoreline in front of the church with a maximum wave height of ~3.5 m and an inundation distance of 165 m, sufficient to inundate the church area.

Additionally, archeological investigations have documented extensive structural damage around Lake Iseo’s shore following the 1222 CE earthquake⁴⁹, supporting the occurrence of another important tsunami event. Together, these historical and archeological pieces of evidence for both events strongly support our comprehensive numerical reconstruction, confirming that delta collapses triggered two exceptionally large catastrophic tsunamis in Lake Iseo over a century apart.

We also investigated the potential preservation of tsunami deposits along Lake Iseo’s shoreline. However, extensive human modification has largely erased natural sedimentary archives. The only remaining undisturbed site, a peatland at the southern tip near Iseo, was cored at multiple locations using a Russian corer. Numerical models, however, indicate minimal wave heights (<1 m) at this site (Fig. 3) due to wave diffraction around Monte Isola, which splits incoming waves, resulting in indirect and attenuated wave propagation toward the southern tip. Consequently, no identifiable tsunami deposits were found at this site, which is consistent with the findings of Zafar et al.⁵⁰, highlighting the importance of wave height and directivity in controlling the spatial distribution of tsunami deposits along lake shores. Other factors, such as localized sedimentation dynamics, erosion, historical peatland exploitation or undocumented disturbances, may also explain the apparent absence of deposits on land.

Discussion

A persistent legacy of tsunami hazard

Land use, the primary driver of increased delta instability at Lake Iseo during the medieval period, has intensified significantly in modern times. After a brief decline following the collapse of the 1222 CE, notably during the Black Death, land use resumed and escalated sharply from 1661 CE onward, peaking during the Industrial era and continuing today³² (Supplementary Fig. 3). Thus, over the past eight centuries, sustained anthropogenic erosion has progressively amplified sediment delivery to the Oglio Delta^{17,32}, increasing its vulnerability to future collapse under seismic or gravitational forces.

Today, the shores of Lake Iseo are among the most densely developed in the Italian Alps, with numerous cities, marinas, and extensive tourist infrastructure. Additionally, Monte Isola, the largest inhabited lake island in Europe, attracts a significant amount of tourist activity. A tsunami comparable in magnitude to the catastrophic events that struck Lake Iseo during the medieval period would cause severe devastation today, given the region’s dense population and shoreline development. The simulations suggest that wave run-up would inundate large sections of the current shoreline, including urban areas and the inhabited shores of Monte Isola (Fig. 3). Critically, warning times for near-field locations would be negligible: waves generated by a collapse of the Oglio Delta would reach the northern shore in less than one minute (Fig. 3). In more distant areas, an early warning system might offer a brief window for evacuation to higher

ground, but it would remain insufficient for an effective response within such a short time frame.

The legacy of intensive agro-pastoral activities in the Italian Alps^{32,36,51,52} affected not only Lake Iseo during the earthquakes of the 12–13th centuries but also other major alpine lakes in the region. Although the southern European Alps have been less systematically studied than the northern and western Alps are, the presence of very thick megaturbidites in the deep basins of Lakes Garda⁵³ and Como²⁵ suggests that steep, sediment-overloaded slopes in both lakes also collapsed during medieval seismic activity, and historical records confirm catastrophic tsunami activity in the region’s lakes^{40,48}. Today, the large perialpine lakes of northern Italy (Garda, Como, and Iseo) feature some of Europe’s most densely developed freshwater shorelines, home to more than 370,000 permanent residents⁵⁴ and welcome tens of millions of visitors annually. Ongoing human-driven erosion in the Italian Alps, which peaked in the 18–19th centuries at its highest levels since the early Holocene⁵², together with active fault systems⁴³, continues to overload steep deltaic slopes, increasing the likelihood of major tsunamigenic collapses.

This human amplified tsunami hazard is not confined to the southern European Alps. Numerous other alpine lakes, including Lake Geneva^{22,24,29}, Lake Sils³⁰, Lake Brienz^{18,20}, and Lake Lucerne^{21,23}, have experienced recurrent tsunamigenic delta collapses during periods of intensified human-induced erosion triggered by seismic shaking, spontaneous slope failure, or external disturbances such as rockfalls. Over the past several centuries, human-driven erosion, primarily from agro-pastoral activities, has reached levels unmatched in the Holocene, driving substantial sediment accumulation in alpine lake deltas^{13–15} and increasing future tsunami hazards.

Similar mechanisms have also been observed outside Europe. For example, in south-central Alaska, Lakes Eklutna, Skilak, and Kenai host multiple deltas that have undergone repeated collapse, with the most recent large tsunamigenic delta collapses triggered by the 1964 megathrust earthquake^{19,31}. In New Zealand, delta collapses have also been identified as the primary source of repeated lake tsunamis²⁷.

All of these worldwide tsunamigenic delta collapses have been attributed to sediment overloading from catchment erosion, so the interplay of land use, sediment overloading, and recurrent seismic or spontaneous delta failures observed at Lake Iseo is a global issue. Soil erosion from human activities, as evidenced by a global synthesis of 632 lake-watershed records, is now at its highest level since the Industrial Era¹⁴, thereby overloading deltaic slopes worldwide. Our multidisciplinary approach supports a holistic hazard assessment of lacustrine environments. Given that the hidden legacy of human land use can lead to large tsunamis, communities around Lake Iseo and in similar lacustrine settings worldwide can better prepare for these low-probability but high-consequence events. The cascading effects observed in Lake Iseo serve as both a cautionary tale and a call to action, underscoring that today’s hazard assessment and land management strategies will shape the disasters of tomorrow.

Methods

Modeling of the Iseo Delta collapse and tsunami

Tsunamis generated by delta collapses in Lake Iseo were modeled in two stages using a one-way coupling approach. First, the dynamics and time evolution of the landslide were simulated using the landslide model. Second, the simulated landslide evolution was converted into time-dependent bathymetric changes that served as inputs to the tsunami model. The tsunami model accounts for these time-varying lake-bed deformations, which are transferred directly to the overlying water column, leading to the generation and propagation of tsunami waves. In this framework, the influence of landslide motion on the water column is explicitly considered, whereas feedback from the generated waves onto the landslide dynamics is neglected. However, hydrodynamic effects such as viscous drag and added-mass forces are

incorporated into the landslide modeling stage prior to coupling with the tsunami model.

Landslide modeling

We simulated delta failure using the two-layer, depth-averaged (2HD) viscoplastic debris-flow model BingClaw, which applies a Herschel–Bulkley rheology and is specifically developed for cohesive subaqueous landslides⁵⁵. BingClaw has been extensively validated against geological observations, including the 8150 BP Storegga landslide⁵⁶ and subaqueous landslides in French Alpine lakes^{47,57}. The model represents the failed mass as two layers: an upper plug layer, in which the sediment moves *en bloc* without internal shear deformation, and a lower shear layer, where deformation occurs once the applied shear stress exceeds the yield strength. Mass balance equations are solved over the entire depth (both layers), whereas momentum equations are solved separately for each layer via a Godunov-type finite-volume scheme. For a detailed description of BingClaw, see Kim et al.⁵⁵.

Landslide dynamics and runout are controlled by several parameters that describe the rheology of the flow. We chose the rheological parameters that gave the best match to the observed runout distance, as well as to the thickness and spatial distribution of the final deposits, guided by the sensitivity analysis of Kim et al.⁵⁵. Runout distance is most sensitive to yield strength⁵⁵. In the present study, yield strength values were constrained via observational runout distances from seismic profiles (Fig. 2c, f). The sediment density and water content were obtained directly from the core data. The simulation of the 1117 CE slide used a yield strength of 25 Pa and a bulk density of 1600 kg/m³, whereas the 1222 CE slide used a yield strength of 7 Pa and a bulk density of 1650 kg/m³. The lower yield strength for the 1222 CE slide reflects its higher water content and greater proportion of coarse sediment (Supplementary Fig. 2). All other parameters, including the non-Newtonian fluidity index, n (0.5), added mass (0.1), frictional drag (0.01), pressure force (1.0), and reference strain rate (100 s⁻¹), were held at the fixed values following Kim et al.⁵⁵ and Zafar et al.^{47,57}. By using all these parameters, we perform landslide simulations and determine the time-dependent runout distance of the slide until it reaches its final depositional position in the deep basin. This output will be used in further tsunami modeling.

Tsunami modeling

Time-dependent bathymetric changes from the landslide model were used to drive wave generation in the tsunami model. We used the two-dimensional depth-averaged nonlinear shallow-water equation (NSWE) model, GeoClaw⁵⁸, to simulate tsunami wave propagation and inundation. GeoClaw is an open-source, widely used tsunami model that has been validated against the National Tsunami Hazard Mitigation Program (NTHMP) benchmark problems⁵⁹ and applied to numerous events with comparisons to tide gauges⁶⁰ and geological data, including those from lakes^{47,50,57}. GeoClaw employs a shock-capturing Godunov-type finite-volume scheme^{61,62} on rectangular grids with adaptive mesh refinement and handles wet/dry interfaces effectively during inundation. For a detailed description of GeoClaw, see LeVeque et al.⁶³. Rectangular computational grids with a cell size of 10 m were used to simulate tsunami wave propagation and inundation, with a Manning roughness coefficient of 0.03. The present-day reference lake level (185.44 m a.s.l.) was used, as there is no evidence of significant lake-level variations during the last ~2 kyr, also considering the nearly constant extent of the marsh area (Torbiere d'Iseo) at the southern edge of Lake Iseo.

Froude number estimation

The initiation of tsunamis is primarily determined by the landslide volume and its initial frontal area. However, the characteristics and intensity of tsunami waves and their interactions with underwater

landslides are also strongly affected by the Froude number (Fr)^{64,65}, which is defined as the ratio of the landslide's velocity to the speed of longwave gravity waves, is given by:

$$Fr = U / \sqrt{gh} \quad (1)$$

where $U = \sqrt{u^2 + v^2}$ represents the landslide's velocity magnitude. The symbols ' g ' and ' h ' denote the gravitational acceleration and the depth of the water, respectively. The most efficient tsunami generation occurs near resonance when $Fr \approx 1$ ⁶⁶.

We calculated the Froude number for the 1117 CE event over the first 200 s of the simulation. The temporal evolution (Supplementary Fig. 5) reveals that during the initial acceleration phase of delta collapse, Fr reached a maximum of ~0.9, approaching the resonant condition ($Fr \approx 1$). This indicates efficient energy transfer from the landslide to surface waves and, consequently, the most efficient tsunami generation. After ~20 s, Fr rapidly decreased to ~0.6 and then gradually declined during runout, reflecting reduced tsunami generation efficiency as the landslide decelerated and propagated into deeper water.

Dispersive sensitivity analysis

To examine dispersion effects, we applied the dispersive tsunami model BoussClaw developed in the framework of modified Boussinesq equations, as suggested by Schäffer et al.⁶⁷ and Schäffer and Madsen⁶⁸. BoussClaw retains accurate dispersion for shorter-wavelength waves by incorporating dispersion terms in the momentum equations via operator splitting: the shallow-water equations are solved with a high-resolution finite-volume scheme, followed by dispersive terms solved with a finite-difference scheme. Wave breaking is represented by switching to the shallow-water equations when the wave-height-to-water-depth ratio exceeds 0.8. Further details are provided in Kim et al.⁶⁹.

We compared the numerical results from both the nondispersive NSWE model and the weakly dispersive Boussinesq model to assess the influence of frequency dispersion on tsunami waveforms. Surface elevations versus distance were extracted along a transect to capture the leading wave at $t = 3.56$ min (Supplementary Fig. 4c), and synthetic gauge time series were analyzed (Supplementary Fig. 4d). Both outputs showed similar waveforms and arrival times for the two models, indicating negligible dispersion. The wavelength, ~5.5 km (Supplementary Fig. 4c), is approximately 22 times the maximum water depth of 250 m. We also evaluated the Stokes–Ursell number⁷⁰, which measures the relative importance of nonlinear and dispersive effects. It characterizes whether wave dynamics are dominated by nonlinear ($U \gg 1$) or dispersive ($U \ll 1$) effects⁷¹ and is defined as follows:

$$U = \left(\frac{\eta}{h} \right) \left(\frac{L}{h} \right)^2, \quad (2)$$

where h is the water depth, η is the wave height, and L is the wavelength. Using a maximum water depth of $h \approx 250$ m, a wave height of $\eta \approx 5$ m, and a wavelength of $L \approx 5.5$ km, we obtained a nonlinearity parameter of $\eta/h \approx 0.02$ and a dispersion parameter of $(h/L)^2 \approx 0.002$. Their ratio yields a Stokes–Ursell number of $U \approx 10$. Together, these results indicate that the tsunami wave was nonlinear and effectively nondispersive in this setting. Consequently, we used only the NSWE model for the analysis of tsunami inundation.

Landslide initiation depth sensitivity analysis

The tsunami simulations presented in Fig. 3 are based on the most plausible reconstructed source geometries (Fig. 2) given the present-day delta morphology. However, to evaluate the sensitivity of tsunami generation to landslide initiation depth, we also tested two alternative source scenarios, S1 and S2, for the 1117 CE event, in which the failed

mass was initiated from depths of 45 m and 75 m along the delta front, respectively. Scenario S1 produced a maximum tsunami height of ~22 m, whereas Scenario S2 produced a maximum height of ~11 m (Supplementary Fig. 6).

Data availability

The simulation data generated in this study have been deposited in the Figshare repository under <https://doi.org/10.6084/m9.figshare.30417256.v1>⁷². This repository includes all necessary output files and scripts to run and reproduce our simulation results.

Code availability

In our study, simulations were conducted using three numerical models. The mass movement model BingClaw can be found in the Zenodo repository <https://doi.org/10.5281/zenodo.11070887>⁷³. The non-dispersive model GeoClaw is available on the Clawpack website (<https://www.clawpack.org/geoclaw>)⁷⁴. The weakly dispersive wave model BoussClaw is accessible at the Zenodo repository <https://doi.org/10.5281/zenodo.11070898>⁷⁵.

References

- Montgomery, D. R. *Dirt: The Erosion of Civilizations, with a New Preface*. 304 (Univ of California press, 2012).
- Fao, I. Status of the world's soil resources (SWSR)—main report. *Food Agric. Organ. U. N. Intergov. Tech. Panel Soils Rome Italy* **650**, 608 (2015).
- Kemp, D.B., Sadler, P.M. & Vanacker, V. The human impact on North American erosion, sediment transfer, and storage in a geologic context. *Nat Commun* **11**, 6012 (2020).
- Olsson, L. et al. Land degradation: IPCC special report on climate change, desertification, land 5 degradation, sustainable land management, food security, and 6 greenhouse gas fluxes in terrestrial ecosystems. In *IPCC special report on climate change, desertification, land 5 degradation, sustainable land management, food security, and 6 greenhouse gas fluxes in terrestrial ecosystems* 1 345–436 (Intergovernmental Panel on Climate Change (IPCC), 2019).
- Nienhuis, J. H. et al. Global-scale human impact on delta morphology has led to net land area gain. *Nature* **577**, 514–518 (2020).
- Renaud, F. G. et al. Tipping from the Holocene to the Anthropocene: how threatened are major world deltas? *Curr. Opin. Environ. Sustain.* **5**, 644–654 (2013).
- Syvitski, J. et al. Earth's sediment cycle during the Anthropocene. *Nat. Rev. Earth Environ.* **3**, 1–18 (2022).
- Edwards, K. J. & Whittington, G. Lake sediments, erosion and landscape change during the Holocene in Britain and Ireland. *CATENA* **42**, 143–173 (2001).
- Fuchs, M. An assessment of human versus climatic impacts on Holocene soil erosion in NE Peloponnese, Greece. *Quat. Res.* **67**, 349–356 (2007).
- Arnaud, F. et al. Erosion under climate and human pressures: an alpine lake sediment perspective. *Quat. Sci. Rev.* **152**, 1–18 (2016).
- Giosan, L. et al. Short communication: massive erosion in monsoonal central India linked to late Holocene land cover degradation. *Earth Surf. Dyn.* **5**, 781–789 (2017).
- Walsh, K. et al. Holocene demographic fluctuations, climate and erosion in the Mediterranean: a meta data-analysis. *The Holocene* **29**, 864–885 (2019).
- Rapuc, W. et al. Human-triggered magnification of erosion rates in the European Alps since the Bronze Age. *Nat. Commun.* **15**, 1246 (2024).
- Jenny, J.-P. et al. Human and climate global-scale imprint on sediment transfer during the Holocene. *Proc. Natl. Acad. Sci.* **116**, 22972–22976 (2019).
- Rapuc, W. et al. Human and climate impacts on the alpine Critical Zone over the past 10,000 y. *Proc. Natl. Acad. Sci.* **122**, e2506030122 (2025).
- Montgomery, D. R. Soil erosion and agricultural sustainability. *Proc. Natl. Acad. Sci.* **104**, 13268–13272 (2007).
- Rapuc, W. et al. Instant sedimentation in a deep Alpine lake (Iseo, Italy) controlled by climate, human and geodynamic forcing. *Sedimentology* **69**, 1816–1840 (2022).
- Gastineau, R., Girardclos, S., Kremer, K. & Anselmetti, F. S. Human-initiated autocyclic delta failures. *Sedimentology* **72**, 45–66 (2025).
- Praet, N. et al. Paleoseismic potential of sublacustrine landslide records in a high-seismicity setting (south-central Alaska). *Mar. Geol.* **384**, 103–119 (2017).
- Girardclos, S. et al. The 1996 AD delta collapse and large turbidite in Lake Brienz. *Mar. Geol.* **241**, 137–154 (2007).
- Hilbe, M. & Anselmetti, F. S. Signatures of slope failures and river-delta collapses in a perialpine lake (Lake Lucerne, Switzerland). *Sedimentology* **61**, 1883–1907 (2014).
- Schnellmann, M., Anselmetti, F. S., Giardini, D., McKenzie, J. A. & Ward, S. N. Prehistoric earthquake history revealed by lacustrine slump deposits. *Geology* **30**, 1131–1134 (2002).
- Nigg, V. et al. Shallow-water tsunami deposits: evidence from sediment cores and numerical wave propagation of the 1601 CE Lake Lucerne event. *Geochim. Geophys. Geosystems* **22**, e2021GC009753 (2021).
- Kremer, K., Simpson, G. & Girardclos, S. Giant Lake Geneva tsunami in AD 563. *Nat. Geosci.* **5**, 756–757 (2012).
- Fanetti, D., Anselmetti, F. S., Chapron, E., Sturm, M. & Vezzoli, L. *Megaturbidite Deposits in the Holocene Basin Fill of Lake Como (Southern Alps, Italy)*. *Paleogeography, Paleoclimatology, Palaeoecology* vol. 259 323–340 (Elsevier, 2008).
- Hilbe, M. & Anselmetti, F. S. Mass movement-induced tsunami hazard on perialpine Lake Lucerne (Switzerland): scenarios and numerical experiments. *Pure Appl. Geophys.* **172**, 545–568 (2015).
- Hughes, K. E., Fitzsimons, S. J. & Howarth, J. D. Lacustrine mass movements in active tectonic settings: Lake tsunami sources in New Zealand's South Island. *Geomorphology* **464**, 109359 (2024).
- Chapron, E., Van Rensbergen, P., Beck, C., Batist, M. de & Paillet, A. Lacustrine sedimentary records of brutal events in Lake Le Bourget (Northwestern Alps-Southern Jura) [Enregistrements d'événements brutaux dans la sédimentation lacustre du Lac du Bourget (Alpes occidentales-Jura méridional)] <https://doi.org/10.3406/quate.1996.2068> (1996).
- Kremer, K. et al. Reconstructing 4000 years of mass movement and tsunami history in a deep peri-Alpine lake (Lake Geneva, France-Switzerland). *Sedimentology* **62**, 1305–1327 (2015).
- Nigg, V. et al. A tsunamigenic delta collapse and its associated tsunami deposits in and around Lake Sils, Switzerland. *Nat. Hazards* **107**, 1069–1103 (2021).
- McCulloch, D. S. *Slide-Induced Waves, Seiching, and Ground Fracturing Caused by the Earthquake of March 27, 1964, at Kenai Lake, Alaska*. 41 (US Government Printing Office, 1966).
- Rapuc, W. et al. Quantitative Evaluation of Human and Climate Forcing on Erosion in the Alpine Critical Zone over the Last 2000 Years. *Quaternary Science Reviews* **268**, 107127 (Elsevier, 2021).
- Anati, E. & Cittadini, T. Valcamonica rock art: a new history for Europe. 208 (1994).
- Gehrig, R. Pollenanalytische Untersuchungen zur Vegetations- und Klimageschichte des Val Camonica 152 (Norditalien, 1997).
- Marziani, G. & Citterio, S. The effects of human impact on the arboreal vegetation near ancient iron smelting sites in Val Gabbia, northern Italy. *Veg. Hist. Archaeobotany* **8**, 225–229 (1999).
- Pini, R. A high-resolution Late-Glacial? Holocene pollen diagram from Pian di Gembro (Central Alps, Northern Italy). *Veg. Hist. Archaeobotany* **11**, 251–262 (2002).

37. Pini, R. et al. Ecological changes and human interaction in Valcamonica, the rock art valley, since the last deglaciation. *Alp. Med. terr. Quat.* **29**, 19–34 (2016).
38. Dal Piaz, G. V., Bistacchi, A. & Massironi, M. Geological outline of the Alps. *Episodes J. Int. Geosci.* **26**, 175–180 (2003).
39. Rovida, A. et al. Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 3.0. <https://www.emidius.eu/AHEAD/study/CPTI15v3> (2020).
40. Guidoboni, E., Comastri, A. & Boschi, E. The “exceptional” earthquake of 3 January 1117 in the Verona area (northern Italy): a critical time review and detection of two lost earthquakes (lower Germany and Tuscany). *J. Geophys. Res. Solid Earth* <https://doi.org/10.1029/2005JB003683> B12309 (2005).
41. Livio, F. A. et al. Active Fault-Related Folding in the Epicentral Area of the December 25, 1222 (Io= IX MCS) Brescia Earthquake (Northern Italy): Seismotectonic Implications. *Tectonophysics* **476**, 320–335 (Elsevier, 2009).
42. Oliveti, I. et al. The Shakemap atlas of historical Earthquakes in Italy: configuration and validation. *Seismol. Res. Lett.* **95**, 21–37 (2023).
43. Michetti, A. M. et al. Active compressional tectonics, Quaternary capable faults, and the seismic landscape of the Po Plain (northern Italy). *Ann. Geophys.* **55**, 969–1001 (2012).
44. Lauterbach, S. C. et al. DecLakes. A sedimentary record of Holocene surface runoff events and earthquake activity from Lake Iseo (Southern Alps, Italy). *The Holocene* **22**, 749–760 (2012).
45. Piccin, A. & Coren, F. Acquisizione e trattamento di dati morfobatimetrici ad alta risoluzione nel bacino del lago Sebino (Lombardia). in *Atti VI conf. Naz. ASITA, Perugia* 5–8 (2002).
46. Bini, A. et al. Morphology and geological setting of Iseo Lake (Lombardy) through multibeam bathymetry and high-resolution seismic profiles. *Swiss J. Geosci.* **100**, 23–40 (2007).
47. Zafar, M. N. et al. Modeling earthquake-induced seiche processes and subsequent homogenite deposition in lacustrine settings. *Earth Planet. Sci. Lett.* **660**, 119348 (2025).
48. Pisano, G. Liber compositus de variis historiis pro diversis utilitatibus lectori proventuris (BAV, Vaticano Latino, 11564, fol. 184r). Biblioteca Apostolica Vaticana (12th century).
49. Gallina, D. La pieve di Sant’Andrea di Iseo (Bs). Dall’analisi stratigrafica e archeologica alla politica edilizia dell’episcopato bresciano tra XI e XII secolo. In *architettura dell’XI secolo nell’Italia del Nord. Storiografia e nuove ricerche* (eds Segagni Malacart, A. & Schiavi, L. C.) 177–197 (ETS, 2013).
50. Zafar, M. N. et al. Strike-slip fault-generated paleotsunamis in Lake Iznik (NW Türkiye): numerical modeling corroborated by coastal deposits. *Geophys. Res. Lett.* **52**, e2025GL117422 (2025).
51. Joannin, S., Magny, M., Peyron, O., Vannière, B. & Galop, D. Climate and land-use change during the late Holocene at Lake Ledro (southern Alps, Italy). *The Holocene* **24**, 591–602 (2014).
52. Comiti, F. How natural are Alpine mountain rivers? Evidence from the Italian Alps. *Earth Surf. Process. Landf.* <https://doi.org/10.1002/ESP.2267> (2012).
53. Gasperini, L. et al. Morphotectonics and late Quaternary seismic stratigraphy of Lake Garda (Northern Italy). *Geomorphology* <https://doi.org/10.1016/j.geomorph.2020.107427> (2020).
54. Italian National Institute of Statistics (ISTAT). Demo. Resident population by municipality, 1 2025. <https://demo.istat.it/app/?i=POS&l=en> (2025).
55. Kim, J., Løvholt, F., Issler, D. & Forsberg, C. F. Landslide material control on tsunami genesis—the Storegga slide and tsunami (8100 Years BP). *J. Geophys. Res. Oceans* **124**, 3607–3627 (2019).
56. Løvholt, F., Bondevik, S., Laberg, J. S., Kim, J. & Boylan, N. Some giant submarine landslides do not produce large tsunamis. *Geophys. Res. Lett.* **44**, 8463–8472 (2017).
57. Zafar, M. N., Dutykh, D., Sabatier, P., Banjan, M. & Kim, J. Numerical reconstruction of landslide paleotsunami using geological records in Alpine Lake Aiguebelette. *J. Geophys. Res. Solid Earth* **129**, e2023JB028629 (2024).
58. Clawpack Development Team. Tsunami numerical code GeoClaw [Software]. Clawpack Development Team. Retrieved from <https://www.clawpack.org/geoclaw> (2020).
59. González, F. et al. GeoClaw results for the NTHMP tsunami benchmark problems. in *Results of the 2011 NTHMP Model Benchmarking Workshop* 135–211 (2012).
60. Adams, L. M. & LeVeque, R. J. GeoClaw model tsunamis compared to tide gauge results, final report November 3, 142 (2017).
61. Dutykh, D., Poncet, R. & Dias, F. The VOLNA code for the numerical modeling of tsunami waves: generation, propagation and inundation. *Eur. J. Mech.-B/Fluids* **30**, 598–615 (2011).
62. LeVeque, R. J. *Finite Volume Methods for Hyperbolic Problems*. Vol. 31 558 (Cambridge University Press, 2002).
63. LeVeque, R. J., George, D. L. & Berger, M. J. Tsunami modelling with adaptively refined finite volume methods. *Acta Numer* **20**, 211–289 (2011).
64. Jiang, L. & LeBlond, P. H. The coupling of a submarine slide and the surface waves that it generates. *J. Geophys. Res. Oceans* **97**, 12731–12744 (1992).
65. Løvholt, F., Glimsdal, S. & Harbitz, C. B. On landslide-tsunami uncertainty and hazard. *Landslides* **17**, 2301–2315 (2020).
66. Harbitz, C.B., Løvholt, F., Pedersen, G. & Masson, D. G. Mechanisms of tsunami generation by submarine landslides: a short review. *Nor. J. Geol. Geol. Foren.* **86**, 255–264 (2006).
67. Schäffer, H. A., Madsen, P. A. & Deigaard, R. A Boussinesq model for waves breaking in shallow water. *Coast. Eng.* **20**, 185–202 (1993).
68. Schäffer, H. A. & Madsen, P. A. Further enhancements of Boussinesq-type equations. *Coast. Eng.* **26**, 1–14 (1995).
69. Kim, J., Pedersen, G. K., Løvholt, F. & LeVeque, R. J. A Boussinesq-type extension of the GeoClaw model - a study of wave breaking phenomena applying dispersive long wave models. *Coast. Eng.* **122**, 75–86 (2017).
70. Ursell, F. The long-wave paradox in the theory of gravity waves. In *Mathematical Proceedings of the Cambridge Philosophical Society* **49**, 685–694 (Cambridge University Press, 1953).
71. Theory and Applications of Ocean Surface Waves | Advanced Series on Ocean Engineering. https://www.worldscientific.com/worldscibooks/10.1142/5566?srsltid=AfmBOorn48DV-bOLdaboNEtA1pZx_Qs6TY2BbiYIL_YzFucnEJDkbVX 1136.
72. Zafar, M. N. Simulation data for human-enhanced tsunami hazard in large lakes. *Figshare* <https://doi.org/10.6084/m9.figshare.30417256.v1> (2025).
73. Kim, J. BingClaw software. Zenodo <https://doi.org/10.5281/zenodo.11070887> (2024).
74. Clawpack Development Team. Tsunami numerical code GeoClaw. <https://www.clawpack.org/geoclaw> (2020).
75. Kim, J. BoussClaw software. Zenodo <https://doi.org/10.5281/zenodo.11070898> (2024).

Acknowledgments

We thank the Nature Reserve Torbiere del Sebino for sampling authorization and help in the field.

Author contributions

P.S., D.D., and M.N.Z. initiated, designed, and coordinated the project. D.D. and P.S. supervised the work. M.N.Z. performed the landslide source reconstruction and numerical modeling, with key contributions from P.S., D.D., W.R., F.A., R.P., and A.P. Available core and seismic reflection data were reanalyzed and incorporated into this study by M.N.Z., W.R., F.A., and P.S. Onshore field investigations were conducted by P.S., R.P., M.N.Z., and A.P. Historical and archaeological records were investigated by P.V. The original manuscript was written by M.N.Z., and all the authors discussed the results and

reviewed and commented on the manuscript. Display items were prepared by M.N.Z. and W.R.

Funding

M.N.Z. gratefully acknowledges the financial support received from the Ministry of Higher Education and Research (MESRI) and the Doctoral School ED MSTII in the form of a PhD scholarship to conduct research for his doctoral thesis. We also acknowledge Université Savoie Mont Blanc, CNRS, and Khalifa University for financial support.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-026-78272-8>.

Correspondence and requests for materials should be addressed to Muhammad Naveed Zafar.

Peer review information *Nature Communications* thanks Filippo Zani-boni, who co-reviewed with Cesare Angeli, Bernd Zolitschka, Stefan Lauterbach, and the other anonymous reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026