First-order loss estimation for subaqueous mass-movement generated tsunamis on perialpine lakes

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Abstract

Subaqueous mass movements can trigger tsunami waves not only in the oceans, but also on lakes. For a few Swiss perialpine lakes, tsunamis have been documented in historical reports (e.g. Cysat 1969; Favrod 1991), mainly caused by earthquake-triggered subaqueous mass movements. In addition, results from numerical modelling show that tsunamis may occur again on perialpine lakes (e.g. Hilbe and Anselmetti 2015). To be prepared for such events, a quantitative risk assessment is essential. Although several authors have tried to quantify marine tsunami risk, the possible impact of lake tsunamis remains understudied. Herein, we leverage recent work that modeled possible earthquake-triggered mass movement tsunami scenarios on the well-investigated Lake Lucerne in Switzerland and proceed to obtain some first-order estimates of possible earthquake- and tsunami-induced economic losses. We use tsunami intensity footprints, in terms of flow depth and momentum flux, conditional on subaqueous mass movements triggered by 475- and 2475-year ground motions. These are overlaid with the built exposure at the village of Buochs-Ennetbürgen, located at the shore of Lake Lucerne. Earthquake and tsunami damage is computed based on fragility and consequence information retrieved from the Earthquake Risk Model of Switzerland (ERM-CH23) and the HAZUS tsunami model. Earthquake and tsunami losses are further contrasted and discussed. This work provides a first analysis of the tsunami risk around perialpine lakes.

1 Introduction

1.1 Background

It is documented that on perialpine lakes, subaqueous and subaerial mass movements (SAQMM) and (SAEMM) have generated destructive lake tsunamis (e.g. Huber 1980; Huber 1982; Hilbe and Anselmetti 2015; Kremer et al. 2021). Many of the mass movements that occurred at the slopes of Swiss lakes were likely triggered by earthquakes (e.g. Schnellmann et al. 2002; Strasser et al. 2013; Reusch et al. 2016), a fact established by the coeval occurrence across various lake basins.

In the context of the research project “TSUNAMI-CH”, the tsunami hazard was for the first time quantitatively analyzed for Swiss lakes. Important results were i) a classification of Swiss lakes according to their tsunami potential (Strupler et al. 2020b), and ii) a generic workflow for the quantitative estimation of the tsunami hazard caused by SAQMM and SAEMM (Strupler et al. 2023). The workflow allows the simulation of the generation, propagation, and inundation effects of lake tsunamis, using hydrodynamical modelling with the freely available software BASEMENT (Vanzo et al. 2021; Vetsch 2020).

To our knowledge, no quantitative loss estimation for tsunamis on perialpine lakes has been conducted yet. However, to mitigate a potential risk, a first-order idea of the frequency and potential consequences of a known hazard are needed. The purpose of this work is to assess the potential economic loss related to tsunami scenarios that are generated by SAQMM for the test site Buochs-Ennetbürgen, located along the
shore of Lake Lucerne, Switzerland. The first-order loss results are further contrasted to the earthquake losses for the study site under the same scenarios, estimated based on the recently released Earthquake Risk model of Switzerland (ERM-CH23) (Wiemer et al. 2023; Papadopoulos et al., submitted).

We use the extents and characteristics of potential SAQMM that are assumed to be triggered by earthquakes with local peak ground acceleration with mean return periods of 475 and 2475 years, respectively (Strupler et al. 2020a), to calculate two tsunami hazard scenarios, using the workflow described in Strupler et al. (2023).

2 Study setting: Lake Lucerne

Lake Lucerne is situated in Central Switzerland, at an elevation of ~ 434 m a.s.l. (Fig. 1). The existence of historical lake tsunami events such as the well investigated and documented 1601 CE and 1687 CE events (Cysat 1969; e.g. Schnellmann et al. 2002; Hilbe and Anselmetti 2015) in combination with the fact that there is a relatively high potential for future SAQMM and SAEMM generating water waves (Strasser et al. 2011; Hilbe and Anselmetti 2015; e.g. Strupler et al. 2020b) makes Lake Lucerne a prime site for lake tsunami hazard and risk investigations.

We selected the case study site “Buochs-Ennetbürgen” (Fig. 1) to do some first-order loss calculations, due to its extended populated area located only few meters above lake shore. In this study, we consider only SAQMM as trigger of tsunamis.

3 Data and methodology

The calculation of a scenario loss requires an intensity footprint, a distributed exposure model, and a vulnerability model. The intensity footprint refers to the spatial distribution of one or several intensity measure(s) (e.g. flow depth and momentum flux in the case of tsunami, or spectral acceleration at multiple periods of vibration in the case of earthquake). The exposure model comprises a geo-referenced database of assets with information such as their characteristics and value. The vulnerability model provides the information needed to associate an intensity value with a loss ratio (economic loss divided by replacement value). The following sections provide information on these model components and their use within this study.

3.1 Tsunami intensity maps

As per FEMA (2022), damage to non-structural components and contents is modeled as a function of flow depth, while damage to structural components, caused by hydrodynamic forces, is modeled as a function of momentum flux.

We use tsunami scenarios that were calculated with the workflow described in Strupler et al. (2023): As input data, the workflow needs the extent and thickness of the historical or future SAQMM, as well as a combined bathymetric and topographic dataset. In this study, we use the characteristics of mass
movements that Strupler et al. (2020a) estimated with a rapid, simplified approach. The mass movements are expected to be triggered at the subaqueous slopes of Lake Lucerne by mean peak ground acceleration (PGA) with median return periods of 475 and 2475 years as per Wiemer et al. (2015). In the study area of Buochs-Ennetbürgen, the PGA values are ~ 0.06 and ~ 0.16g, respectively.

Wave generation, propagation and inundation was calculated with BASEMENT, version 3, a freely available tool for hydro- and morphodynamic modelling (Vetsch et al. 2020; Vanzo et al. 2021). To consider landslide volume uncertainty, a total amount of 100 Monte Carlo sampled landslide source scenarios with various sediment thickness log-normal distributions are used for calculating wave generation. A log-normal transformed standard deviation of 25% of the mean thickness of the landslide sources zonated by Strupler et al. (2020a) was assumed. Propagation of the wave was modelled using the depth-averaged shallow water equations. For each simulation run, the flow depth ($h$) and momentum flux ($mf$) was calculated. From all the simulations, the 5th, 50th (median), and 95th percentiles of the flow depth ($h$) and momentum flux ($mf$) (Figs. 2 and 3) were calculated and plotted on a grid with a spatial resolution of 10 m.

### Table 1

<table>
<thead>
<tr>
<th>Quantile</th>
<th>RP 475: inundated area [m²]</th>
<th>RP 475: buildings located in inundated area</th>
<th>RP 2475: inundated area [m²]</th>
<th>RP 2475: buildings located in inundated area</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th</td>
<td>38'900</td>
<td>3</td>
<td>276'600</td>
<td>125</td>
</tr>
<tr>
<td>50th</td>
<td>52'300</td>
<td>4</td>
<td>486'900</td>
<td>267</td>
</tr>
<tr>
<td>95th</td>
<td>92'500</td>
<td>21</td>
<td>698'100</td>
<td>419</td>
</tr>
</tbody>
</table>

The inundated area estimated for EQ-triggered mass movement tsunamis (median scenario) with RP = 475 years in the study area is ~ 5*10⁴ m², and ~ 5*10⁵ m² for RP = 2475 years (Table 1), thus ~ 10 times more.

For the median scenario of return periods of 475 years, most flow depth cells show values in the ranges of 0.01 to 2m and 2m to 5m (around equal amount). For the median scenario of return periods of 2475 years, most flow depth cells show values in the range of 2 to 5 m. For both return periods, only very few grid cells located directly along the shore show values greater than 5m (Figs. 3 and 4).

### 3.2 Earthquake ground motion intensity maps

Earthquake occurrence, ground motion, damage, and loss estimation is modelled here based on ERM-CH23 (Wiemer et al., 2023; Papadopoulos et al., under review). The details of that model are not within the scope of this work, hence the reader is referred to these publications for further information.
The tsunami scenarios studied here are tied to landslides induced by rock PGA values expected for return periods of 475 and 2475 years. At the study area where we analyse tsunami damage, the expected values are of 0.062g (475 years) and 0.161g (2475 years). To contrast and/or combine earthquake and tsunami scenarios, we therefore need to identify ground motion intensity map realizations that are consistent with this constraint. To do so, ERM-CH23 is used to carry out an event-based probabilistic analysis using the OpenQuake engine (Pagani et al., 2014). This involves first the generation of a large number (1.5 million here) 1-year long stochastic earthquake catalogues, followed by the generation of associated random ground motion fields for each stochastic rupture. Subsequently, earthquake-induced losses are estimated as a function of the ground motion input at the locations of buildings. It should be noted that for this work, we use only the part of ERM-CH23 that uses spectral acceleration (and not macroseismic intensity) as intensity measure.

Here, from the stochastic set of events, we then identify those associated with ground motion fields that featured rock PGA values (at Buochs-Ennetbürgen), in line with the values associated with the two tsunami scenarios. More precisely, we collected the events associated with PGA values between 0.052g and 0.072g at the predetermined location for the first scenario, and between 0.141g and 0.181g for the second scenario. To ensure plausibility of the selected ground motion fields, the latter were generated using the intra-event residual spatial correlation model of Jayaram and Baker (2009).

### 3.3 Exposure data

To assess the impact of the generated earthquake and tsunami intensity realizations, the latter needs to be overlaid with a geo-referenced database of assets (e.g. building objects) that comprise the exposure model. The exposure dataset, apart from the location of assets, contains information regarding their value (i.e. replacement cost) and characteristics (e.g. building material, height, year of construction) that define the structural typology. The structural typology is used to characterize the vulnerability of each building. In this study, the exposure model has been compiled as part of ERM-CH23 based on a geo-referenced building database of more than 3 million objects across Switzerland. Material attributed were then assigned based on field surveys carried out in several Swiss cities (Wiemer et al. 2023). The study area contains n = 1971 buildings, mostly of 1-story height (Fig. 1).

The structural typology classification (taxonomy) used in ERM-CH23 differs from the one proposed by the HAZUS Tsunami model. Since the vulnerability of buildings to tsunami loads is modelled according to the HAZUS Tsunami model (FEMA, 2022; see following section), a correspondence between the ERM-CH23 and HAZUS material classes is necessary. Table 2 shows the assumed mapping between the two models.
<table>
<thead>
<tr>
<th>ERM-CH23 material</th>
<th>Description</th>
<th>HAZUS material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3</td>
<td>Unreinforced Masonry (rubble stone)</td>
<td>URM</td>
<td>Unreinforced Masonry Bearing Walls</td>
</tr>
<tr>
<td>M4</td>
<td>Unreinforced Masonry (dressed stone)</td>
<td>URM</td>
<td>Unreinforced Masonry Bearing Walls</td>
</tr>
<tr>
<td>M5</td>
<td>Unreinforced Masonry (old bricks)</td>
<td>URM</td>
<td>Unreinforced Masonry Bearing Walls</td>
</tr>
<tr>
<td>M6</td>
<td>Unreinforced Masonry (RC floors)</td>
<td>URM</td>
<td>Unreinforced Masonry Bearing Walls</td>
</tr>
<tr>
<td>RCW</td>
<td>Shear wall</td>
<td>C2</td>
<td>Concrete Shear Walls</td>
</tr>
<tr>
<td>T</td>
<td>Timber</td>
<td>W1</td>
<td>Wood, Light Frame</td>
</tr>
<tr>
<td>S</td>
<td>Steel</td>
<td>S1</td>
<td>Steel Moment Frame</td>
</tr>
<tr>
<td>Ind</td>
<td>Industrial</td>
<td>S1</td>
<td>Steel Moment Frame</td>
</tr>
</tbody>
</table>

### 3.4 Vulnerability model and loss calculation

The vulnerability of each structural typology is typically characterized by means of a fragility model and a damage-to-loss (or consequence) model. The former associates intensity measure values to damage state exceedance probabilities (Grossi and Kunreuther 2005), whereas the latter associates each distinct damage state to a value of normalized loss (or loss ratio, i.e. repair cost divided by total replacement cost).

#### 3.4.1 Fragility functions

Tsunami fragility functions can be derived (i) empirically from post-tsunami assessments, (ii) expert judgement-based, or (iii) analytically by numerically simulating structural damage (Charvet et al. 2017). The capacity of a building to withstand tsunami-forces is dependent on structural design, construction material, and ground floor characteristics, among others (UNESCO-IOC 2011). While damage induced as a result of flow depth (“flood damage”) primarily affects nonstructural systems and contents of a building, lateral forces due to the tsunami flow (“flow damage”) are the primary cause of damage to the building structure (FEMA 2022). For previous tsunami events worldwide, empirical fragility curves have been developed (Valencia et al. 2011; e.g. Mas et al. 2012; Suppasri et al. 2012). Empirical fragility curves are developed by observing and correlating measured damage in the field to IM observations. However, as no considerable event has occurred on Lake Lucerne since the well-documented 1601 CE and 1687 CE tsunamis on Lake Lucerne (Cysat 1969; e.g. Schnellmann et al. 2002; Hilbe and Anselmetti 2015), no empirical fragility curves can be derived for the shorelines under current development. In such situations, analytical fragility functions can be used, which are developed by calculating the damage based on
numerical simulation. In this study, we use the analytical functions of the HAZUS Tsunami model (FEMA 2022). HAZUS provides distinct fragility curves, i.e. curves that relate intensity measure (IM) values (depth, momentum flux) with damage state exceedance probabilities for structural and non-structural building components, as well as for contents. On the other hand, the earthquake fragility model is retrieved from ERM-CH23 and is defined in terms of spectral acceleration at 0.3 and 0.6 s (see Wiemer et al. 2023).

Fragility curves are given in the form of Eq. 1, which show the cumulative probability of exceeding a damage state $DS_i$ conditioned on the IM (e.g. flow depth $h$ or momentum flux $mf$).

$$P[ds \geq DS_i | IM] = \varphi \left( \frac{\ln(IM) - \ln(IM_i)}{\beta} \right)$$

(1)

where $\varphi$ is the standard normal cumulative distribution function, and $IM$ and $\beta$ are the median values and log-standard deviations respectively of the building fragilities for each damage state $i$. $DS_i$ is the damage state represented by the fragility function and $ds$ is the actual damage state of the building. The parameters $IM$ and $\beta$, in the tsunami case, are provided by HAZUS for the various building typologies that were matched to the ERM-CH23 equivalent ones.

The probability of being in $DS_i$ is then given by Eq. 2

$$P(DS_i | IM) = P(ds \geq DS_i | IM) - (ds \geq DS_{i+1} | IM)$$

(2)

### 3.4.2 Damage scale harmonization and damage-to-loss model

Given that we make use of vulnerability models from two somewhat different frameworks, some inconsistencies arise that need to be smoothened before comparing and/or combining earthquake and tsunami loss metrics. Below, we summarize some of the important discrepancies and steps taken towards harmonization.

1. The definition of damage states and damage-to-loss models differs between HAZUS and ERM-CH23. HAZUS foresees 4 distinct damage states (DS; slight, moderate, extensive, complete), although it also assumes that tsunami actions cannot produce what HAZUS classifies as slight damage. ERM-CH23 follows the EMS-98 (Grüental, 1998) damage scale, which distinguishes into 5 distinct damage states (slight, moderate, substantial, very heavy, collapse).

2. ERM-CH23 and HAZUS use different damage-to-loss models. Apart from the loss ratio values that naturally differ, ERM-CH23 is defined for 5 damage states as per the previous point, and also foresees a different model for each building structural typology. On the other hand, HAZUS is defined
for 4 damage states and differences are foreseen for building of different occupancies (residential, commercial, etc).

These differences need to be harmonized in order to provide a fair comparison between the earthquake- and tsunami-induced loss, and two to be able to combine them. To this end, the following assumptions are deemed appropriate: First of all, we decide to use the damage-to-loss model of ERM-CH23 (Wiemer et al. 2023; Table 3), given that it has been compiled with the Swiss construction practice in mind. The loss ratios for damage states 1 to 3 are anyways found within the same range between the two models, so a correspondence seems appropriate. The last damage state (DS5 in ERM-CH23 and DS4 in HAZUS) induces in both cases full loss (100%). The very heavy damage (DS4) of ERM-CH will be assumed to be reached only as a result of earthquake actions.

Moreover, the HAZUS tsunami model foresees a final damage state damage-to-loss ratio of 100% for contents, as opposed to ERM-CH23 (as well as the HAZUS earthquake model), which assume that 50% of the contents value (as opposed to structural and nonstructural value) can be retrieved even if the building reaches DS5. This creates some ambiguity as to the level of loss to be assigned to a building that has reached DS5 as a result of the combined action of earthquake and tsunami. Here, we will assume a 100% loss if the tsunami action has triggered exceedance of the DS5 threshold, and 50% loss if it was the earthquake action that caused it.

Table 3
Damage-to-loss model, based on ERM-CH23, used in the study. The ranges for the structural or nonstructural components refer to different building structural typologies.

<table>
<thead>
<tr>
<th>DS1</th>
<th>DS2</th>
<th>DS3</th>
<th>DS4</th>
<th>DS5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural and nonstructural loss ratio [%]</td>
<td>1.5–2.8</td>
<td>6.9–15.1</td>
<td>32.5–47.1</td>
<td>53.3–88.5</td>
</tr>
<tr>
<td>Contents loss ratio [%]</td>
<td>1</td>
<td>5</td>
<td>15</td>
<td>25</td>
</tr>
</tbody>
</table>

### 3.5. Damage and loss calculation workflow

The assessment of damage under the combined action of earthquake and tsunami largely relies on the recommendations of HAZUS, with some minor adjustments in the workflow to accommodate the harmonization steps previously outlined and the objectives of this study which are to assess losses for the conditional scenarios previously described. The workflow followed here is summarized in Fig. 4.

Firstly, for each of the multiple earthquake ground motion intensity maps generated as described in section 3.2, damage state probabilities (due to earthquake) are computed, for each building, from the relevant fragility model and the ground motion input at its site. Likewise, the tsunami damage state probabilities can be computed from the tsunami fragility model and the input flow depth and momentum flux at the location of the building. The next step in our framework is to use these damage state probabilities (which should sum up to 1.0) to randomly sample a damage state for earthquake and one
for tsunami for all the buildings. The combination to derive the final damage state, is adapted from HAZUS, and carried out according to the rules laid out in Table 4.

<table>
<thead>
<tr>
<th>Final damage state</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS1</td>
<td>$D_{EQ1}$</td>
</tr>
<tr>
<td>DS2</td>
<td>Either $D_{EQ2}$, or $D_{TS2}$</td>
</tr>
<tr>
<td>DS3</td>
<td>Either $D_{EQ3}$, or $D_{TS3}$ or ($D_{EQ2}$ and $D_{TS2}$)</td>
</tr>
<tr>
<td>DS4</td>
<td>Either $D_{EQ4}$, or ($D_{EQ3}$ and $D_{TS3}$)</td>
</tr>
<tr>
<td>DS5</td>
<td>Either $D_{EQ5}$, or $D_{TS4}$ or ($D_{EQ4}$ and $D_{TS3}$)</td>
</tr>
</tbody>
</table>

Lastly, the associated economic loss for the entire exposure is obtained by applying the ERM-CH23 damage-to-loss model, as described in the previous section, and multiplying the relevant loss ratios with the building and contents replacement costs. The simulation of the damage states (and subsequent loss) is carried out $n = 100$ times to achieve statistical stability.

4 Results and Discussion

Earthquake-induced loss

As indicated in Table 1, the extent of inundation of the tsunami associated with a 2475-year PGA is significantly larger compared to the 475-year PGA scenario. This difference is also reflected in the loss estimates obtained for the two scenarios. Table 1 reports the sample median earthquake losses (referring to the total of all structural, nonstructural, and contents losses) for the two scenarios. For the 475-year PGA scenario, 1597 events with associated random ground motion intensity maps were selected as described in section 3.2, leading to a median earthquake loss of 7.51 M CHF. On the other hand, for the 2475-year PGA scenario, 257 events were found within the specified PGA range, leading to a median earthquake-induced loss of 54.45 M CHF.

Tsunami-induced loss

On the tsunami side, the first PGA-scenario (475 years mean return period) would cause losses of 0.14, 0.31, or 0.65 M CHF depending on the quantile of tsunami load that is used. Equivalently, the second scenario (2475 years mean return period) would cause tsunami-induced losses of 4.34, 20.61, or 65.41 M CHF (Table 1).

Combined earthquake and tsunami loss
Table 5
Earthquake-induced losses associated with the two considered PGA scenarios

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>475 year PGA scenario</td>
<td>0.052g – 0.072g</td>
<td>1597</td>
<td>7.51</td>
<td>0.14/0.31/0.65</td>
</tr>
<tr>
<td>2475 year PGA scenario</td>
<td>0.141g – 0.181g</td>
<td>257</td>
<td>54.45</td>
<td>4.34/20.61/65.41</td>
</tr>
</tbody>
</table>

While the above estimates reflect the predicted losses should one of the two studied perils occur, in reality earthquake and tsunami actions might coincide (especially on peri-alpine lakes, where many mass-movement triggered tsunamis are caused by earthquakes) and affect the same buildings. The losses estimated when both perils are accounted for amount to 7.65–8.15 M CHF (depending on the tsunami actions quantile) for the 475-year PGA scenario and to 58.57-119.23 M CHF for the 2475-year PGA scenario. The effect of the possible tsunami on the losses experienced in Buochs-Ennetbürgen can be more visibly seen in Fig. 5, which shows the distribution of loss for the 2475-year PGA scenario. Under the 5% quantile tsunami intensity assumption, the tsunami-attributed loss is only a small fraction of the sustained damage. On the other hand, we see that in the case of the 95% quantile tsunami intensity, the tsunami actions could more than double the losses sustained due to the earthquake alone.

Of course, the above statements refer solely to the nearshore locality of Buochs-Ennetbürgen. A strong earthquake is expected to cause widespread damage over a larger area, whereas a lake tsunami will impact the exposure in susceptible areas surrounding the lake. Even within the limited extent of Buochs-Ennetbürgen, the spatial distribution of loss is expected to be much more localized for the tsunami peril. In Fig. 6, we show the estimated loss ratio across a 500m x 500m grid for the PGA = 0.16g scenario and the 50% tsunami intensity quantile. The tsunami actions affect only the coastal areas of the community, where in individual grid cells, they can amplify the earthquake-only loss by a factor of up to 1.65. A larger effect is of course seen in Fig. 7, which shows the same maps for the 95% quantile intensity case. In that case, tsunami actions can increase the loss in specific locations by a factor of up to 12.5.

4.2 Limitations

The objective of this paper was a first-order investigation of the possible economic losses resulting from earthquake-triggered lake tsunami. While our results provide a first estimate of the potential lake tsunami impact, several limitations should be mentioned, most of which can be improved in future work.
• The investigation here is limited to two tsunami intensity scenarios from Strupler et al. (2023) that were calculated based on a rapid estimation of the subaqueous mass movement hazard (Strupler et al. 2020a). The latter uses many simplifications (e.g. slope stability model, geotechnical and sedimentological and earthquake assumptions), which are described in the referred publication. While epistemic uncertainty pertaining to the tsunami volume as a result of uncertain sediment thickness is investigated, the mass movement trigger threshold in terms of PGA is deterministic.

• The use of scenarios constrains us in merely looking at the impact of tsunami conditional to realizations of rock PGA value. Assigning a frequency or probability of these events should be explored in the future, as well as a full-blown probabilistic risk assessment combining the actions of earthquakes and lake tsunamis.

• For assessing the tsunami impact, here we make use of the fragility model of HAZUS that has been derived with the U.S. in mind. It has been shown that existing fragility functions can vary considerably (Tarbotton et al. 2015). Ideally, a model tailored to the Swiss building stock could be developed in the future.

• Entrained building debris created by the earthquake may increase tsunami flow damage. To test these effects, detailed hydrodynamical and structural modelling would be needed.

6 Conclusions and outlook

For the first time, subaqueous landslide-tsunami induced losses around perialpine lakes were estimated quantitatively in this work. The results obtained may be used for cost-benefit analyses of tsunami hazard mitigation measures.

Although this study was only conducted on a selected lake, in a relatively small area with a small number of buildings, it becomes evident that a certain lake tsunami risk exists for the nearshore locations. Especially for tsunamis caused by subaqueous mass movements expected for mean return periods of 2475 years, the combined earthquake and tsunami damage can be more than an order of magnitude larger than the earthquake damage alone at certain locations. However, compared to earthquake damage that can span across a large area, the tsunami damage is very localized, focusing on the nearshore area. To conclude, in many nearshore areas, the financial tsunami risk should be considered.

Future work will seek to integrate mass-movement tsunami risk and earthquake risk under a unified multi-hazard and multi-risk framework. Whereas in this study only economical damage was considered, causalities may be estimated in a next step. Given the availability of flow depth and momentum flux maps, tsunami loss scenarios and risk may be calculated for other perialpine lakes, and prioritizations can be made among the lakes. Also, other tsunamigenic processes such as subaerial mass movements may be considered.

Declarations
Acknowledgments

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Competing Interests

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

Author Contributions

All authors contributed to the study design. Data preparation, calculations, and writing were conducted by MS and ANP. All authors read and approved the final manuscript.

References


Figures
Figure 1

Study site Buochs-Ennetbürgen. inlet: overview Lake Lucerne. Bathymetric and topographic data: swisstopo. Buildings from ERM-CH23, colour-coded according to the number of stories
Figure 2

Flow depth intensity maps (5th, 50th, and 95th quantiles) for return periods of 475 yrs (top) and 2475 yrs (bottom).
Figure 3

Momentum flux intensity maps (5th, 50th, and 95th quantiles) for return periods of 475 yrs (top) and 2475 yrs (below)
Figure 4

Workflow for estimation of PGA-scenario economic loss due to earthquake and tsunami loads
Figure 5

Distribution of economic loss at Buochs-Ennetbürgen, conditional on $PGA_{rock} \approx 0.16$ g if earthquake-only or earthquake and tsunami actions are considered.
Figure 6

Earthquake-only (top left), tsunami-only (top right) and combined earthquake and tsunami (bottom left) loss ratios computed over a 500 m x 500 m grid for the PGA = 0.16 g scenario. The bottom right panel shows the ratio of the combined loss over the earthquake-only loss. The tsunami losses here refer to the 50% percentile tsunami intensity.
Figure 7

Earthquake-only (top left), tsunami-only (top right) and combined earthquake and tsunami (bottom left) loss ratios computed over a 500 m x 500 m grid for the PGA = 0.16 g scenario. The bottom right panel shows the ratio of the combined loss over the earthquake-only loss. The tsunami losses here refer to the 95% percentile tsunami intensity.