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Sebastian Krastel · Jan-Hinrich Behrmann
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Submarine Mass Movements and Their Consequences

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Chapter 44
Modeling Submarine Landslide-Generated Waves in Lake Ohrid, Macedonia/Albania

Katja Lindhorst, Sebastian Krastel, Cord Papenberg, and Mohammed Heidarzadeh

Abstract We study potential tsunami hazards associated with submarine landslides in Lake Ohrid, Macedonia/Albania. The transboundary Lake Ohrid located on the Balkan Peninsula shared by Macedonia and Albania is considered to be the oldest-continuously existing lake in Europe (2–5 Ma), though the age and the origin are not completely unraveled to date. Previous studies by means of hydroacoustic methods have shown that the western margin of Lake Ohrid has a long history of mass wasting. Based on seismic data, slide deposits are found in different stratigraphic levels as well as on the lake floor where they have affected a large area. This study is focused on the well-studied Udenisht Slide Complex covering an area of 27 km^2 within the southwestern part of Lake Ohrid. The Udenisht slide is by far the largest mass movement with an average thickness of 30–40 m and an estimated volume of about 0.11 km^3. It is therefore well within the limits of submarine landslides that are known to be capable of triggering tsunamis. Using numerical modeling, the propagation of a landslide-generated tsunami with an initial wave height of more than 5 m has been calculated. Run-up heights estimated for coastal communities around the lake are moderate in the north (2–3 m) can reach up to 10 m directly at the site where the slide initiated. This study is a first generation of landslide tsunami hazard assessment for Lake Ohrid and further detailed modeling is recommended for the region.

Keywords Lake Ohrid • Submarine landslide • Tsunami • Numerical modeling

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K. Lindhorst (✉) • S. Krastel (✉)
Institute of Geosciences, Christian-Albrechts Universität zu Kiel, Kiel, Germany
e-mail: klindhorst@geophysik.uni-kiel.de; skrastel@geophysik.uni-kiel.de

C. Papenberg
Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

M. Heidarzadeh
Cluster of Excellence – The Future Ocean, Institute of Geosciences, Christian-Albrechts University zu Kiel, Kiel, Germany

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44.1 Introduction and Study Area

Lake Ohrid situated on the Balkan Peninsula (Fig. 44.1) in a tectonically-formed basin is most likely the oldest lake in Europe (2–5 Ma, Albrecht and Wilke 2008). Surrounded by high mountains, the surface of Lake Ohrid is located at an altitude of 693 m above sea level. It extends 30 km north-south and 15 km east-west covering an area of about 360 km^2.

The total water volume of Lake Ohrid is 55 km^3; maximum water depth reaches 293 m (Popovska and Bonacci 2007). Previous geophysical investigations showed the importance of Lake Ohrid as a valuable archive to study the sedimentary evolution of a graben system over several million years (Lindhorst 2012).

Lake Ohrid has been formed as a pull-apart basin in Late Miocene with subsequent E-W extension within the South Balkan Extensional Regime (Burchfiel et al. 2008; Lindhorst 2012). The sedimentary infill within the central part of the basin indicates that Lake Ohrid existed continuously since its initial formation (Lindhorst et al. 2010). A first chronological model suggests that the oldest sediments within the deepest part of the basin are at least 2 Ma old (Lindhorst 2012). Acoustic data show widespread mass wasting deposits.

In this study we investigate the tsunamigenic potential of landslides within Lake Ohrid using numerical modeling. First, we briefly summarize mass wasting features within the basin. Afterwards we present results of our modeling approach with

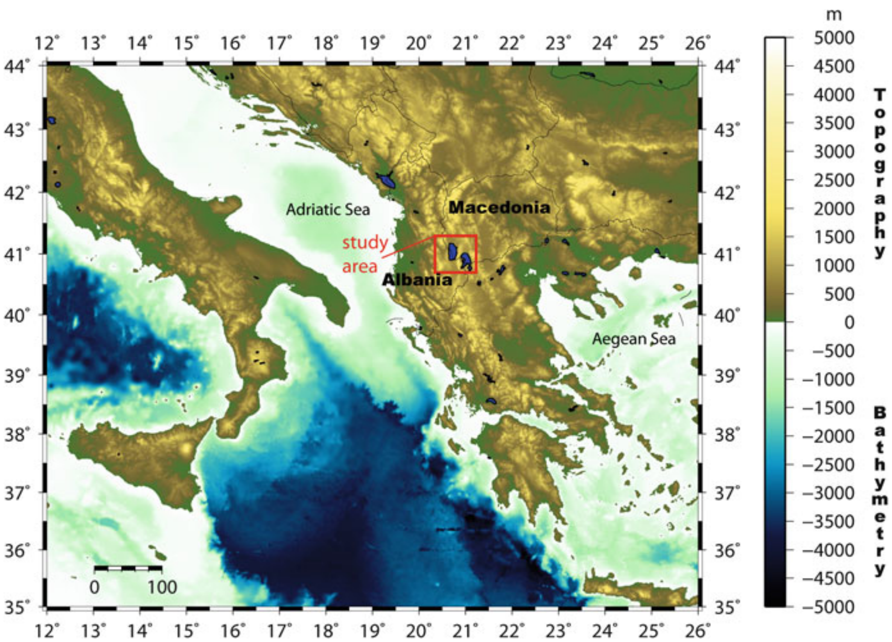

Fig. 44.1 General location map of Lake Ohrid on the Balkan Peninsula

a focus on wave amplitudes at several stations along the shore of Lake Ohrid. Our results increase the general understanding of landslide-generated hazard within active basins and can be seen as a case study for other deep lakes with steep flanks especially in regions with high seismic activities such as the alpine lakes.

44.1.1 Mass Wasting in Lake Ohrid

Slide deposits are widespread within the basin and can be found at different stratigraphic levels indicating that Lake Ohrid has a long history of mass wasting. Possible trigger mechanisms for submarine sliding events within Lake Ohrid were discussed in Lindhorst et al. (2012). The fact that Lake Ohrid is located within a seismically active region and the location of the Udenisht slide is along the active margin point to an earthquake as the most likely trigger for the Udenisht slide event. For example, Wagner et al. (2012) showed that an earthquake in the sixth century most likely triggered a slide in the northwestern part of Lake Ohrid.

Seismic cross sections of the southwestern part of Lake Ohrid show several chaotic units interpreted as mass wasting deposits within the youngest sedimentary succession (Lindhorst et al. 2012). In total, six slide deposits stacked on top of each other have been mapped. Up to 75 m-thick sediments overlay the oldest slide deposits (Lindhorst et al. 2012). The Udenisht slide complex is the most prominent subaquatic failure event in Lake Ohrid. Sediment echosounder profiles across the sliding area only show a thin sedimentary cover. Taking the sedimentation rate into account it was suggested that the event is younger than 1,500 years (Lindhorst et al. 2012). The sliding area can be identified by means of morphological data as shown in Fig. 44.2. The Udenisht slide covers almost 10 % of the entire lake surface. The Udenisht slide has a long run-out distance. Slide deposits are up to 50 m thick (Fig. 44.2). The volume of the slide is estimated to be $\sim$0.11 km^3 (Lindhorst et al. 2012). Interpretation of the slide morphology suggest that the slide can be classified as a retrogressive submarine mass movement with at least two sub-events and sudden failures of major blocks in the upper part of the slide area (Lindhorst et al. 2012). Although a distinct head wall of the slide has not been detected, we found evidence that the major event was initiated in shallow water depth. In 2009 a bathymetric survey was carried out by means of an ELAC Seabeam 1180 multibeam device resulting in a high resolution topography map (Fig. 44.2). The Udenisht slide area is characterized by an upper slope area bounded by distinct sidewalls and a run-out area where slide deposits up to a thickness of 60 m can be found (Lindhorst et al. 2010, 2012). Furthermore, the present topography excludes that the Udenisht slide was triggered onshore. Seismicity along an active fault trending in NW-SE direction and crossing the upper part of the sliding area, has been interpreted as a trigger for a sub-event in a water depth of about 120 m (Lindhorst 2012).

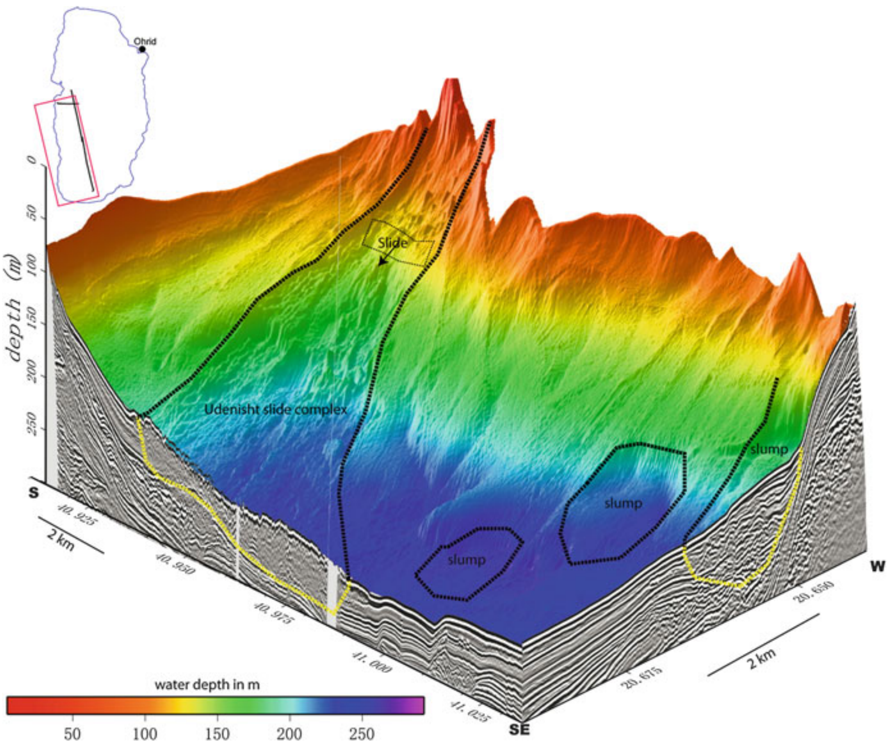

Fig. 44.2 Bathymetric map of the southwestern part of Lake Ohrid showing the morphology of the Udenisht slide complex. Two seismic cross sections showing the slide deposits of the Udenisht slide (*yellow dashed line* in S-N direction) and the slump (E-W profile) further to the north that we used for evaluating input parameters of the modeled tsunami. Two additional slumps along the western margin are marked

44.1.2 Numerical Approach

We use the numerical model TUNAMI-N2 (Imamura et al. 2006; Yalçiner et al. 2004) to simulate the propagation of long waves generated by possible submarine landslides within Lake Ohrid. Developed at the Tohoku University in Japan by Fumihiku Imamura and Nobou Shuto, TUNAMI is one the famous international numerical codes validated with both laboratory and field tsunami data (Yeh et al. 1996).

Tsunami modeling is usually composed of three steps of (1) generation, (2) propagation and (3) inundation. Here, we prevent the waves from inundation on dryland by imposing a vertical wall near the shoreline. To estimate the run-up heights at the main coastal communities around Lake Ohrid, we calculate tsunami wave height at offshore water depth and then apply an empirical equation to estimate the run-up heights. In our numerical simulations, wave evolution beyond water depth of 20 m is prohibited, and then empirical equations are used to estimate run-up heights. Therefore, near-shore wave phenomena such as wave breaking are not considered here. This may imply an over-estimation of the run-up heights.

44.1.3 Initial Tsunami Wave

The initial tsunami wave amplitude will be build up during the acceleration time of the underwater slump. Combined information from high resolution bathymetric and seismic data within the area of the Udenisht slide provide input parameters to constrain the exact location, water depth, slide direction, and the geometry of the slide. However, the initial failure mechanism is difficult to reconstruct because we do not find a distinct headwall today. In order to overcome this problem, we assume that the Udenisht slide initially started as a slump similar to those observed further to the North (Fig. 44.2). Based on this assumption we apply the semi-empirical formulas proposed by Watts et al. (2003) and Grilli and Watts (2005) for our numerical modeling of landslide tsunamis.

The modeled submarine slide is located on the upper slope in a water depth of 120 m of the Udenisht slide complex and moves about 200 m downslope (Fig. 44.2). We further assume that a slide block rotates around a very small angle so that the movement can be described as a translation parallel to the slope. We do not account for deformation of the sliding block during the short acceleration time (t_0) until the maximum depression at the water surface is reach and the initial tsunami wave has been build-up. We assume a specific density of 1,900 g/cm^3 and slide geometry with width of 2,500 m, a length of 500 m, and a thickness of about 50 m resulting in a volume of 0.0625 km^3 for the simulated sliding block. This volume is half the volume of the Udenisht slide deposits (Lindhorst et al. 2012), which we consider as realistic initial slide volume because seismic data show significant entrainment of underlying sediments during slide propagation. The time t_0 until the maximum surface depression was generated is 14.7 s. The resulting wave has a wavelength $\lambda_0 = 510$ m and the characteristic wave height is 5.20 m. We calculated an initial acceleration of $a_0 = 0.8$ m/s^2, a maximum velocity of $u_{max} = 11.4$ m/s, a characteristic distance of motion of $S_0 = 170$ m, and a small angular displacement of $\Delta\Phi = 0.54$ rad.

44.2 Results

44.2.1 Wave Propagation and Estimated Run-Up Heights

The propagation of the modeled tsunami wave is shown in Fig. 44.3. Our modeled mass wasting event induces a tsunami wave reaching Pogradec, Sveti Naum, Gradiste, Ohrid, and Struga after 0.5, 4, 4.5, 8, 10 min, respectively (Fig. 44.4).

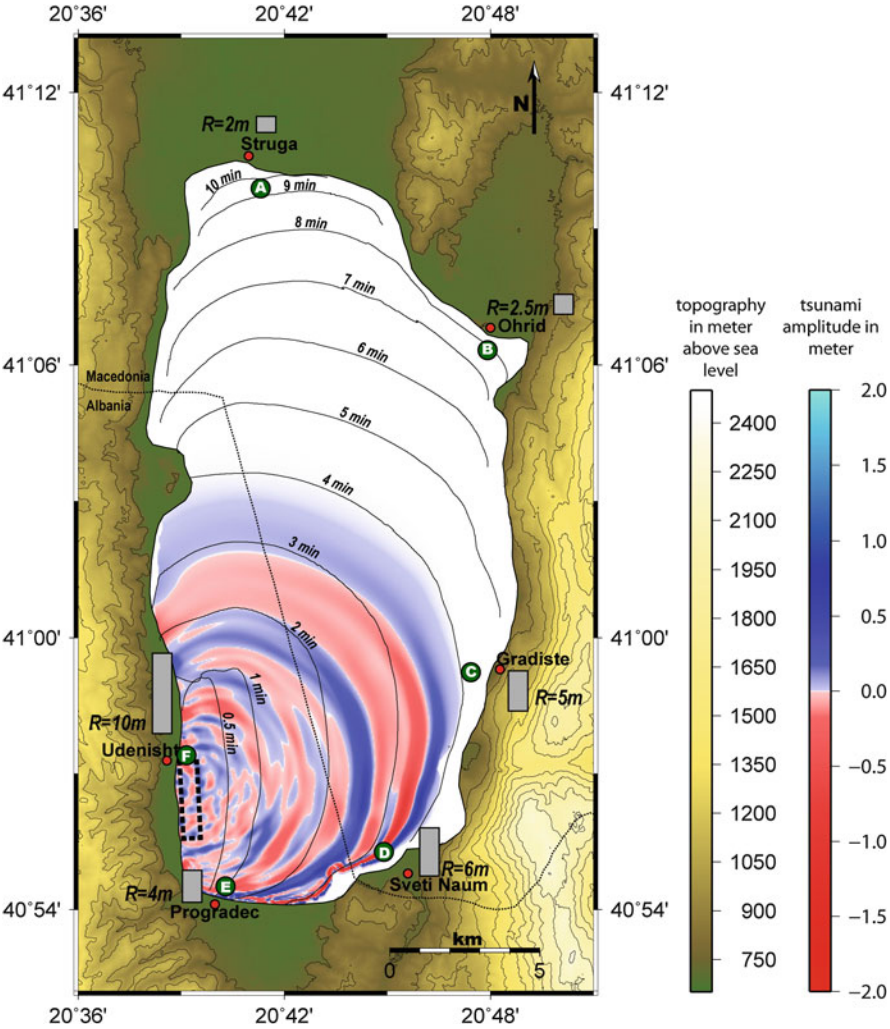

Fig. 44.3 Tsunami wave distribution (*red* and *blue colored*) in Lake Ohrid after 4 mins. Isolines show wave propagation after initiation at the slide location (*dashed square*) over a time period of 10 mins. After that time the tsunami has reached all the coastlines. *Grey bars* indicate run-up height normalized to the maximum run-up at Udenisht. *Green dots* are the virtual tidal gauge stations (Fig. 44.4)

Waves hit the coast at Udenisht immediately after failure occurs (Fig. 44.4). The maximum wave heights at the virtual gauge stations off Udenisht, Progradec, Sveti Naum, Gradiste, Ohrid, and Struga are 75, 60, 120, 60, 23, and 13 cm, respectively. The time histories of tsunami waves at selected locations are shown in Fig. 44.4. As shown, the artificial gauges are located at different water depths of 22, 18, 20, 18, and 20 m.

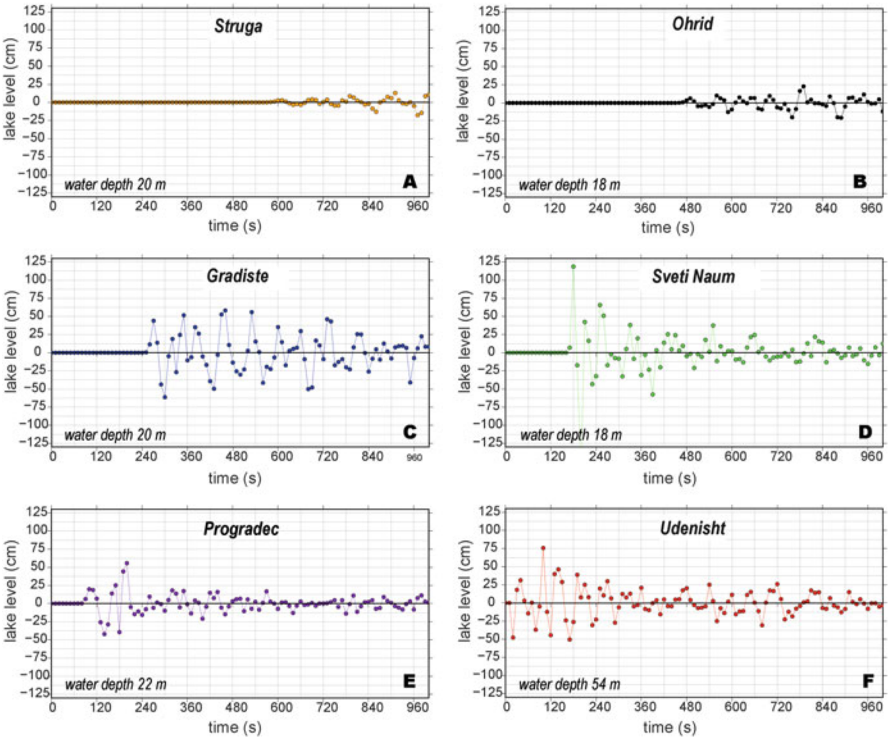

Fig. 44.4 Time histories of tsunami waves at some artificial gauges. Gauge locations are shown in Fig. 44.3

In general the maximum wave heights at Struga and Ohrid are relatively small (<25 cm). The highest waves are measured at Sveti Naum at a water depth of 18 m (Fig. 44.4). Table 44.1 presents our estimation of run-up values using two empirical equations. Whereas the first equation only considers the wave amplitude at a certain water depth and must be considered as a very simple approach to get a first impression of run-up heights at the coast. The second formula is an empirical approach including more parameters such as the slope angle and gives a more realistic estimation of run-up heights. In our cases we assume that the slope angles offshore Udenisht and Gradiste are greatest (∼4°) because they are located along the steep sides of Lake Ohrid. The slope angles in the north are small (∼2°) and for the southern region we assume medium slope values (∼3°). According to Table 44.1, in Udenisht, which is closest to the slide, the estimated run-up heights are greatest (2 and 10 m, Fig. 44.3). Run-up heights in Ohrid (0.5 and 2.5 m) and Struga (0.35 and 2 m) are moderate (Fig. 44.3). In the south the estimated run-up is about 5 m for the second formula (Fig. 44.4).

Table 44.1 Estimation of run-up values using empirical equation

Location	Offshore surface elevation (m)	Water depth (m)	Slope angle (°)	R1 (m)[a]	R2 (m)[b]
Udenisht	0.76	54	4	1.8	10
Pogradec	0.6	22	3	0.8	4
Sveti Naum	1.2	18	3	2	6
Gradiste	0.6	20	4	1.2	5
Ohrid	0.23	18	2	0.5	2.5
Struga	0.13	20	2	0.35	2

[a]The empirical equation by Ward and Asphaug (2003) was used: $\mathrm{R1} = \sqrt[5]{\mathrm{A(d)}^4} \times \sqrt[5]{\mathrm{d}}$, where A(d) is the tsunami amplitude at water depth d

[b]The equation proposed by Ward and Day (2007): $R2 = 3.26 \times H_0 \times (\tan\beta)^{0.42} \times \left(\frac{A_0}{H_0}\right)^{0.41}$, in which H_0 is the offshore water depth in meters, A_0 is the wave amplitude at the water depth of H_0 in meters, β is the slope of the beach, and R is runup height in meters

44.3 Discussion and Conclusion

In order to discuss results of our modeled tsunami wave distribution across Lake Ohrid we compare our estimated run-up value to an empirical formula of Lynett and Liu (2005). In their approach they calculated run-up heights by taking the geometry, submergence depth and slope angle of the failure area into account to estimate a run-up at the coast closest to the submarine landslide event. The equation by Lynett and Liu (2005) gives a run-up value of about 6 m which is close to the values presented here.

According to a morphological analysis, the tsunamigenic potential for the Udenisht slide has been characterized as low (Lindhorst et al. 2012). A long run-out distance of slide material and the fact that the Udenisht slide has been characterized as a retrogressive event with at least two sub-events further reduce the absolute volume of individual failure events. However, this study illustrates that, in general, sub-lacustrine mass failure events as observed within the modern lake floor morphology inhibit a tsunamigenic potential. Results from our numerical modeling presented here show that an underwater slump with a shape similar to that in the northwestern part located at the site of the Udenisht slide is capable to trigger a tsunami wave. Our preliminary modeling shows that this wave would propagate across the entire lake in about 10 min but would have small to moderate estimated run-ups at the cities of Ohrid and Struga (see Table 44.1). At the village of Udenisht and in the southern area of Lake Ohrid we find that the estimated run-ups are large enough to cause significant damages along the coast and are hence a potential hazard for the coastal communities. The time between landslide and tsunami arrival at Udenisht, Pogradec, Sveti Naum, and Gradiste is less than 5 min.

For our numerical solution we assume a simplistic scenario with the following assumptions: (1), a simple geometry of the sliding block (2) non retrogressive behavior of the slide, (3) the present of an intact block comparable to a slump, (4) a short horizontal displacement of ~200 m, and (5) a submergence depth of about 120 m. A slump-type failure was considered in our modeling because, according to Watts et al. (2005), it has a higher potential to trigger a tsunami than submarine slides. The effect of retrogressive behavior of a landslide would reduce the maximum surface elevation and lead to smaller amplitudes (Bondevik et al. 2005; Harbitz et al. 2006). On the other hand, intense slide deformation in shallow water may increase coastal run-up by more than a factor of 2 and 3 (Grilli and Watts 2005). Hence tsunamis of significant height would be triggered, if further failures occur at the uppermost part of the Udenisht slide area.

In order to evaluate the influence of slide volume and initial submergence depth to the initial wave height we ran the tsunami model with higher and lower slide volumes as well as with higher submergence depth as input parameters than presented here which would then effect the coastal amplification. We found that the initial wave height increases dramatically if the tsunami initiates in shallower water depth. We considered these heights as unrealistic for Lake Ohrid because such an event during the last 2,000 years would have been mentioned in primary sources. Because our model does not allow wave breaking effect we could only simulate a tsunami in water depth greater than 50 m. The highest variability in input parameters is slide volume. Although we have a good estimation of the volume that got deposited after the failure along the western margin but it is uncertain whether these deposits are evidences for one single event. In addition our morphological data indicates that the Udenisht slide is a complex system of more than one event that is different in size and submergence depth. In general, an increase in volume would also increase the initial wave height and subsequently higher damages around the coast of Lake Ohrid.

In conclusion, this study gives a first impression of the tsunamigenic potential of sub-lacustrine mass movement events which are common within Lake Ohrid and have been found in different stratigraphic levels. Our study suggests that a potential tsunami hazard within Lake Ohrid cannot be neglected although our preliminary modeling showed that the run-up values would be small. This approach, however, points to the urgent need for more sophisticated modeling approaches for landslide generated tsunamis in Lake Ohrid and comparable lakes.

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References

Albrecht C, Wilke T (2008) Ancient Lake Ohrid: biodiversity and evolution. Hydrobiologia 615:103–140. doi:10.1007/s10750-008-9558-y

Bondevik S, Løvholt F, Harbitz C, Mangerud J, Dawson A, Svendsen J (2005) The Storegga Slide tsunami—comparing field observations with numerical simulations. Mar Petrol Geol 22:195–208

Burchfiel B, Nakov R, Dumurdzanov N, Papanikolaou D, Tzankov T, Serafimovski T, King R, Kotzev V, Todosov A, Nurce B (2008) Evolution and dynamics of the Cenozoic tectonics of the South Balkan extensional system. Geosphere 4:918

Grilli ST, Watts P (2005) Tsunami generation by submarine mass failure. I: modeling, experimental validation, and sensitivity analyses. J Waterw Port Coast Ocean Eng 131(6):283–297

Harbitz C, Løvholt F, Pedersen G, Masson D (2006) Mechanisms of tsunami generation by submarine landslides: a short review. Nor J Geol 86:255–264

Imamura F, Yalciner AC, Ozyurt G (2006) Tsunami modelling manual. UNESCO IOC international training course on Tsunami Numerical Modelling

Lindhorst K (2012) Neotectonic and sedimentary evolution of Lake Ohrid (Albania/Macedonia): acquisition and interpretation of new hydro-acoustic and seismic data. Unpublished PhD thesis, Christian-Albrechts-Universität zu Kiel, Kiel

Lindhorst K, Vogel H, Krastel S, Wagner B, Hilgers A, Zander A, Schwenk T, Wessels M, Daut G (2010) Stratigraphic analysis of lake level fluctuations in Lake Ohrid: an integration of high resolution hydro-acoustic data and sediment cores. Biogeosciences 7:3531–3548. doi:10.5194/bgd-7-3651-2010

Lindhorst K, Gruen M, Krastel S, Schwenk T (2012) Hydroacoustic analysis of mass wasting deposits in Lake Ohrid (FYR Macedonia/Albania). In: Submarine mass movements and their consequences. Springer, Dordrecht, pp 245–253

Lynett P, Liu PL-F (2005) A numerical study of the run-up generated by three-dimensional landslides. J Geophys Res 110(C3):C03006

Popovska C, Bonacci O (2007) Basic data on the hydrology of Lakes Ohrid and Prespa. Hydrol Process 21(5):658–664

Wagner B, Francke A, Sulpizio R, Zanchetta G, Lindhorst K, Krastel S, Vogel H, Daut G, Grazhdani A, Lushaj B (2012) Seismic and sedimentological evidence of an early 6th century AD earthquake at Lake Ohrid (Macedonia/Albania). Climate Past 8:2069–2078

Ward SN, Asphaug E (2003) Asteroid impact tsunami of 2880 March 16. Geophys J Int 153(3):F6–F10

Ward SN, Day S (2007) Tsunami balls: a granular approach to tsunami runup and inundation. Commun Comput Phys 3(1):222–249

Watts P, Grilli S, Kirby J, Fryer G, Tappin D (2003) Landslide tsunami case studies using a Boussinesq model and a fully nonlinear tsunami generation model. Nat Hazards Earth Syst Sci 3(5):391–402

Watts P, Grilli S et al (2005) Tsunami generation by submarine mass failure. II: predictive equations and case studies. J Waterw Port Coast Ocean Eng 131:298

Yalçiner A, Pelinovsky E, Talipova T, Kurkin A, Kozelkov A, Zaitsev A (2004) Tsunamis in the Black Sea: comparison of the historical, instrumental, and numerical data. J Geophys Res 109(C12):C12023

Yeh HH-J, Liu PL, Synolakis C (1996) Long-wave runup models: Friday Harbor, USA, 12–17 September 1995. World Scientific, Singapore