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1 **Tsunamis generated by subaqueous volcanic explosions in Taal**
2 **Caldera Lake, Philippines**

3

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14

15 **Abstract** Volcanic subaqueous explosions can generate hazardous tsunamis, especially in lakes. In this paper,
16 we simulate different scenarios of subaqueous explosions and related tsunamis in Taal Caldera Lake (Luzon,
17 Philippines). Taal volcano is one of the most active volcanoes in Southeast Asia, and eruptive processes are
18 mostly explosive. We test different energies of explosions at eight different explosion sites in the lake. The initial
19 water surface displacement (η_0) generated by the explosion is estimated as a function of explosion energy at a
20 given depth. We estimate the tsunami travel times, maximum wave heights and wave periods at the shoreline.
21 This type of hazard is typically neglected and our work has important implications for hazard assessment around
22 Taal Lake. Due to fast propagation of tsunamis in the lake (waves typically crossing the lake in less than 10
23 minutes), there is only a short time available for issuing a warning. For $\eta_0 \leq 50$ m, wave heights at the shoreline
24 are less than 2 m with a non-dispersive numerical model, and less than 0.5 m with a dispersive model, whatever
25 the explosion depth and location. Powerful explosions with $\eta_0 \gg 100$ m generate wave heights greater than 2 m
26 all around the lake and local peaks higher than 10 m.

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31

32 **Introduction**

33

34 Subaqueous volcanic eruptions represent only 8% of all recorded eruptions but they are
35 particularly deadly (~20% of all fatalities associated with historical volcanism: Mastin and
36 Witter, 2000). Hazards related to eruptions through surface water include phreatomagmatic
37 explosions, base surges, tephra fall (from ash to blocks), lahars (e.g. lake outburst, dam
38 failure), and tsunamis or seiches. In enclosed basins or lakes such as Taal Lake in the
39 Philippines (cf. Fig.1), tsunamis are referred to as the initial waves, and the seiche as the later-
40 stage harmonic resonance within the lake (Ichinose et al. 2000; Freundt et al. 2007). We thus
41 prefer using the term tsunami rather than seiche. During a subaqueous eruption, tsunamis can
42 be generated by different processes such as a pyroclastic flow (e.g. pyroclastic density current
43 resulting from the collapse of a Plinian column), slope instability (landslides on the crater
44 walls), and the explosion itself (Paris, 2015). The mechanisms of interaction between a
45 pyroclastic flow and water as well as the conditions required to generate a tsunami remain
46 partly elusive due to a lack of observations and experimental data (Paris, 2015).

47 On the contrary, the theory of waves generated by subaqueous explosions is well documented
48 (Le Méhauté, 1971; Mirchina & Pelinovsky, 1988; Duffy, 1992; Le Méhauté & Wang, 1996;
49 Egorov, 2007). This particular type of tsunami consists of two main waves followed by
50 smaller undulations propagating radially from the source, as demonstrated by experiments and
51 numerical simulations (e.g. Le Méhauté & Wang, 1996; Kedrinskii, 2005; Torsvik et al.,
52 2010; Ulvrova et al., 2014 & 2016). The water is initially pushed upward (Fig. 2), forming a
53 crater with a cylindrical bore that expands radially to form the leading wave, followed by a

54 wave trough. Initial surface displacement (i.e. maximum height of the bore) can be estimated
55 directly as a function of explosion energy at a given water depth (Le Méhauté, 1971), or
56 indirectly using the size of the submerged volcanic crater formed by the successive explosions
57 (Sato & Taniguchi, 1997; Goto et al., 2001). The water crater collapses as in a dam break
58 model, generating a steep cone of water in the centre that turns to a second cylindrical bore
59 (Le Méhauté & Wang, 1996). Subaqueous explosions typically generate short-period waves
60 compared to earthquakes, and most of the time the impact in the far-field is limited (Latter,
61 1981; Begét, 2000; Paris, 2015). The Myojin-Sho (Japan) submarine eruption in 1952
62 generated waves with amplitudes of less than 1.5 m at 130 km from the volcano, while near
63 the source a survey vessel was capsized (Nakano et al., 1954). In shallow-water lakes, runup
64 inland can be locally high, as illustrated by the 1996 tsunami in Karymskoye Lake (Belousov
65 et al., 2000). The nature of subaqueous volcanic explosions is controlled by a range of
66 physical parameters such as the water depth, geometry of the crater, and complex magma-
67 water interactions (Kokelaar, 1986; Wohletz, 1986; Morrissey et al., 2010). While many
68 Surtseyan-type phreatomagmatic explosions are not tsunamigenic, violent explosions of the
69 Taalian eruptive style (Kokelaar, 1986) have the potential to generate hazardous tsunami
70 waves, especially on lakes (Falvard et al., 2018). Experimental studies (Craig, 1974)
71 demonstrated that maximum wave heights occur for a two-third submerged explosion, i.e. an
72 explosion at two thirds of the total water depth towards the lake bed. The amplitudes of the
73 incoming waves at this critical depth are twice as high as those for explosions at a lower
74 critical depth (fully submerged). In the case of a subaqueous volcanic explosion, the explosion
75 depth d compared to the total water depth D in the vicinity of the eruptive vent is thus a
76 critical parameter (Fig. 2).

77 In this paper, we simulate tsunamis generated by subaqueous explosions in the Taal Caldera
78 Lake (Luzon Island, Philippines, cf. Fig. 1). Historical eruptions at Taal volcano have

79 regularly produced tsunamis (Paris et al., 2014; Delos Reyes et al., 2018), including
80 sublacustrine eruptions suchg as the 1716 eruption. It is thus of primary importance to
81 consider tsunami hazards in Taal lake. Here, we provide the first detailed case-study of
82 tsunami hazards related to subaqueous explosions in the lake.

83

84 **Historical eruptions and tsunamis at Taal volcano**

85

86 Taal volcano is located in the southern part of Luzon Island, Philippines (Fig. 1). It is one of
87 the most active volcanoes in Southeast Asia (Delos Reyes et al., 2018). About two million
88 people live less than 35 km from the volcano, including thousands of people living along the
89 shores of Taal Caldera Lake and Taal Island (Delos Reyes et al., 2018). The lake is an
90 important source of fresh water and food (fish-farming), as well as being a recreational area
91 (Ramos 2002).

92 Historical volcanism (33 identified eruptions) has been concentrated on Taal volcanic island
93 (Delos Reyes et al., 2018), which is a post-caldera composite edifice within the 25 × 30 km-
94 wide Taal Caldera Lake. The spatial distribution of the eruptive vents is controlled by NE-SW
95 and NW-SE tectonic structures intersecting at Taal volcanic island (Listanco, 1997). Eruptive
96 styles range from hydrothermal to Plinian, with most of the eruptions being dominated by
97 phreatomagmatic explosions (including phreatoplinian ones). Pyroclastic flows, base surges
98 and ash falls are the primary hazards at Taal volcano. Lakeshore communities were affected
99 by base surges and ash falls during the major historical eruptions (e.g. 1754 eruption). At least
100 five historical eruptions generated tsunamis in the lake (1716, 1749, 1754, 1911, and 1965)
101 (Delos Reyes et al., 2018). The 1716, 1749, 1754 and 1911 eruptions were described by Maso
102 and Saderra (1904, 1911), and the 1965 eruption was studied by Moore et al. (1966). The

103 1731 sublacustrine eruption might have been tsunamigenic, but there is no clear mention of
104 waves in the lake during this eruption (Maso and Saderra, 1904).

105 The 1716 eruption was also sublacustrine. Descriptions collected by Maso and Saderra (1904)
106 situate the eruption in the southern basin of the caldera lake, near the southeastern point of
107 Taal Island. A “great commotion in the earth” stirred up the water in the lake, “forming
108 immense waves which lashed the shores” (Maso and Saderra, 1904). Waves inundated the
109 southwestern shore of the lake up to 17 m inland.

110 As for the 1716 eruption, the origin of the waves observed during the 1749 eruption remains
111 unclear. This violent phreatomagmatic eruption (VEI 4) lasted three months and severely
112 impacted the northern and northeastern shores of the lake (Delos Reyes et al., 2018). One
113 earthquake led to land subsidence in the northeastern part of the caldera (near Tanauan).
114 Explosions were located in the main crater of Taal Island (Fig. 1), with a possible extension to
115 coastal or sublacustrine vents near the northeastern point of the island.

116 The 1749 eruption was closely followed by a Plinian eruption in 1754 (Delos Reyes et al.,
117 2018). Twelve people were killed by roof collapse (due to intense ash falls) and waves on the
118 western shore of the lake. Tsunamis were observed during the third and fourth phases of the
119 eruption. However, few descriptions of the waves are available (Maso and Saderra, 1904,
120 1911; Delos Reyes et al., 2018).

121 The 1911 phreatomagmatic to phreatoplinian eruption is better documented. Villages on the
122 western shore of the lake were hit by waves three meters high and 20-50 people were
123 drowned (Maso and Saderra, 1911). Since the eruption was not sublacustrine, subaqueous
124 explosions cannot be the cause of the tsunami. Nor did the earthquakes of the initial phase
125 generate tsunamis. Thus, as for the 1754 Plinian eruption, a pyroclastic flow mechanism is
126 more likely (Delos Reyes et al., 2018). However, atmospheric shock waves generated by the
127 strongest explosions (Pratt, 1911) are another possible source mechanism of the tsunamis.

128 Moore et al. (1966) also related the tsunamis observed during the 1965 eruption to shock
129 waves, although the transfer of energy from air to water (or phase-coupling) operates mostly
130 on large areas of deep water (Yokoyama, 1987), i.e. larger and deeper than Taal Caldera
131 Lake.

132 The initial Strombolian phase of the 1965 eruption was followed by a phreatomagmatic phase
133 that opened a new crater on the southwestern flank of Taal Island (Moore et al., 1966, Delos
134 Reyes et al., 2018). Many of the 190-355 fatalities occurred when tsunami waves capsized
135 boats containing residents fleeing from Taal Island to the western shore of the lake (near
136 Agoncillo). The waves inundated areas up to 4.7 m above the level of the lake (Moore et al.,
137 1966).

138

139 **Methods**

140

141 We have selected eight different sites for simulated explosions in Taal Caldera Lake (Fig. 1):
142 three sites in deep water (>100 m water depth), and five sites corresponding to submerged
143 eruptive vents in shallower water (<70 m water depth). Note that one of the sites is located
144 near the possible location of the 1716 sublacustrine eruption (Fig. 1). Following the method
145 proposed by Torsvik et al. (2010) and Ulvrova et al. (2014, 2016), the initial surface
146 displacement generated by the explosion is estimated as a function of explosion energy at a
147 given depth d , using the empirical formula of Le Méhauté and Wang (1996):

$$148 \quad \eta_0 = c E^{0.24} \quad (\text{Eq. 1})$$

149 where η_0 is the vertical initial surface displacement in meters, E the energy of explosion in
150 joules, and c a constant. According to the explosion yield and water depth, two cases are
151 distinguished (Le Méhauté and Wang, 1996): (1) $c = 0.0143$ if $6.15 \times 10^{-4} < d/E^{1/3} < 1.85 \times 10^{-2}$
152 (where d is the depth of explosion in meters); or (2) $c = 0.0291$ if $d/E^{1/3} < 6.15 \times 10^{-4}$. We

153 assume that the explosion occurs at the rim of the submerged crater, which corresponds to an
154 optimal explosion depth in terms of tsunami generation (Fig. 2). Explosions deeper inside the
155 crater would be less tsunamigenic, but the extent of the influence of this parameter remains to
156 be tested.

157 Explosion energy E is estimated following the empirical relationship given by Sato and
158 Taniguchi (1997):

$$159 E = 3.56 \times 10^7 R^3 \quad (\text{Eq. 2})$$

160 where R is the radius of the volcanic crater in meters (Fig. 2). Data from experimental and
161 volcanic explosions varying over 14 orders of magnitude up to $E \sim 10^{17}$ J (corresponding to a
162 crater radius up to $R \sim 1.5$ km) were used for fitting (see Fig. 2 in Sato & Taniguchi, 1997; and
163 Fig. 5 in Goto et al., 2001). We assume that the size of the crater reflects the most powerful
164 explosion at shallow depth (Goto et al., 2001; Taddeucci et al., 2010), regardless of the
165 cumulated energy of all explosions that participated in the formation of the crater. In fact, the
166 morphology of the crater often results from multiple vertically and horizontally-migrating
167 explosions (Sonder et al., 2015; Valentine et al., 2015). Thus, assuming that the diameter of
168 the crater corresponds to the size of the largest explosion at an optimal depth could lead to an
169 overestimation of the explosion energy (Valentine et al., 2014; Sonder et al., 2015). The
170 diameters of the craters on Taal Island range from 90 to 1700 m and the submerged volcanic
171 cones observed on the bathymetry apparently fall in the same range. Crater diameters selected
172 for the simulations range from 200 to 1500 m (Table 1), corresponding to explosion energies
173 $3.5 \times 10^{13} \leq E \leq 1.5 \times 10^{16}$ J, and initial surface displacements $30 \leq \eta_0 \leq 200$ m that were tested
174 for each explosion site. Explosions corresponding to crater diameters lower than 90 m ($E <$
175 3.5×10^{12} J) do not produce waves on the shores of the lake.

176 All numerical simulations were performed using COMCOT (Cornell multi-grid coupled
177 tsunami model: Liu et al., 1998) solving for the non-linear shallow water equations, and

178 FUNWAVE-TVD solving for the fully non-linear Boussinesq-type wave equations (Kirby et
179 al., 1998; Tehranirad et al., 2013). The shallow water equations are valid for horizontal
180 wavelengths greater than ~5 times the water depth. Boussinesq models are able to reproduce
181 the effects of non-linearity (e.g. amplitude dispersion) and frequency dispersion in the case of
182 intermediate-to-deep water waves (up to wavelengths equivalent to water depth). Simulations
183 were all stopped at the shoreline and the inundation phase is thus not simulated, because both
184 models have intrinsic limitations in modelling the nearshore hydrodynamics.

185 The simulations were performed using a 546×496 grid with an initial resolution of 100 m. The
186 grid was obtained by combining the bathymetry displayed in Ramos (2002) and SRTM
187 topography (Shuttle Radar Topography Mission, Farr et al., 2007). In order to have a
188 homogenous circular water crater at the apron of the explosion and to avoid artificial
189 directivity of propagation, grid resolution was refined to 25 m in some cases. Wave heights
190 and arrival times at the coast are calculated at 12 virtual tide gauge stations distributed all
191 around the lake (Fig. 1).

192

193 **Results**

194

195 Tsunami propagation in the lake

196

197 Simulated waves travel through the lake at velocities between 20 and 40 m/s, which
198 correspond to the typical velocity of shallow water waves in 50-170 m water depth.
199 Consequently, waves propagate faster in the southern basin, which is deeper (a third of its
200 area being deeper than 160 m) than the northern basin (water depth < 105 m). In our
201 simulations, there is no significant difference between the shallow water (non-dispersive) and
202 the Boussinesq (dispersive) models in terms of wave velocity (Fig. 3). For identical explosion

203 parameters (location, energy, water depth), both models give similar wave arrival times at a
204 particular coastal site (e.g. Ambulong and Balete on Fig. 3). The velocity of propagation of a
205 tsunami in the lake is mostly controlled by the water depth, and secondarily by the explosion
206 energy (i.e. initial surface displacement). As an example, an explosion at a water depth of 50
207 m with an initial surface displacement $\eta_0 = 50$ m generates a leading wave that arrives at
208 Agoncillo (Fig. 4) one minute later compared to a case with $\eta_0 = 200$ m.

209 Due to the short distance between the tsunami sources (i.e. explosion sites) and the shore of
210 the lake, all simulated tsunamis propagate in less than 10 minutes across the whole lake (Fig.
211 5). In the southern basin, wave arrival times range between 1 and 5 minutes when the
212 explosion is located in the same basin. The southern coast of Taal Island is inundated 1-2
213 minutes after the explosion. The southwestern (Agoncillo, San Nicolas) and eastern shorelines
214 (Balete) of the lake are reached in 2-5 minutes, depending on the energy and location of an
215 explosion in the southern basin. Propagation of waves from one basin to another is slowed by
216 shoals, especially in the narrow strait west of Taal Island (Fig. 1). Waves generated by
217 explosions in the southern basin reach the main localities of the northern basin (Laurel,
218 Talisay) in 5-9 minutes. As explained above, waves propagate slightly slower in the shallower
219 northern basin. However, typical wave arrival times are similar (2-5 minutes) because the
220 northern basin is also slightly smaller than the southern one. Explosions in the northern basin
221 invade the southern basin after 4 minutes of propagation and hit the eastern and southwestern
222 shorelines in 5-7 and 8-10 minutes, respectively (Fig. 5).

223 Note that oscillations of the lake surface may last for several hours after the explosion due to
224 resonance effect (i.e. seiche). For instance, waves with an amplitude of up to 20 cm persist in
225 both basins for more than 3 hours after an explosion at 50 m water depth in the southern basin
226 ($\eta_0 = 115$ m).

227

228 Wave heights at the shoreline

229

230 Maximum wave height (H_{max}) calculated at the shoreline of the lake increases with increasing
231 initial surface displacement η_0 at the source (Fig. 6). For similar explosion parameters (energy
232 and depth), the wave heights at the shorelines are not significantly different from one basin to
233 another. However, shoals between the two basins reduce by a factor of two to ten the
234 amplitude of the waves in the opposite basin to that of the explosion (Figs. 7 and 8). Wave
235 heights at the shoreline rapidly decrease with distance from the explosion site (Fig. 9).

236 For $\eta_0 \leq 50$ m, wave heights calculated at the different virtual tide-gauges are less than 2 m
237 with the non-dispersive model, and less than 0.5 m with the dispersive model. The
238 overestimation of wave heights calculated by the non-dispersive model is particularly marked
239 (typically a factor of two) for explosions with $\eta_0 \leq 80$ m in the deep southern basin (Fig. 9),
240 because the non-dispersive model is not able to faithfully reproduce the propagation of waves
241 that are relatively short compared to water depth.

242 Wave heights up to 4 m (non-dispersive) and 2 m (dispersive) at ~5 km from the explosion
243 site are obtained with $\eta_0 = 80$ m (or $110 \leq \eta_0 \leq 130$ m for very shallow explosions). An
244 explosion at 50 m depth with $\eta_0 = 110$ m in the northern basin generates waves up to 2-3 m on
245 Napayong Island (Fig. 1), whereas a similar explosion at 160 m depth in the southern basin
246 produces wave heights up to 7-8 m on the same island. For $\eta_0 > 110$ m there are fewer
247 differences between the non-dispersive and dispersive models in terms of wave heights at the
248 shoreline. For $110 \leq \eta_0 \leq 130$ m, wave heights up to 5 m are recorded at ~5 km from the
249 explosion site, and even 10 m on the eastern coast of Taal Island. The most powerful
250 explosions ($\eta_0 = 200$ m) generate waves up to 15-20 m high on the coasts of Taal Island and
251 12 m on the other coasts of the lake. Figure 10 shows a sensitivity test for η_0 versus wave
252 height for explosions situated near the 1716 eruption site (cf. submerged cone southeast of

253 Taal Island on Fig. 1). The wave heights calculated both in the northern and southern basins
254 increase exponentially with increasing η_0 (i.e. with increasing explosion energy E for a given
255 depth d).

256

257 Wave spectrum

258

259 Using a dispersive Boussinesq-type model allows both the non-linearity and frequency
260 dispersion effects to be reproduced. Spectral analysis of the virtual tide gauge records
261 produced by this model shows that three kinds of wave periods can be distinguished. Short-
262 period waves (70-130 s) are superimposed on longer-lived intermediate-period waves (200-
263 260 s), and longer periods (550-750 s) are detected in the case of deep explosions (>100 m
264 water depth). Figures 11 and 12 display examples of a wavelet power spectrum and
265 periodogram at two different virtual tide gauge stations (Fig. 11: northern basin; Fig. 12:
266 southern basin) for an explosion at 105 m water depth in the northern basin ($\eta_0 = 120$ m). As
267 wave period, amplitude and velocity are linked, different wave scenarios can be distinguished,
268 depending on the geometry of the source (i.e. the explosion) and bathymetry. The leading
269 wave is usually highest at a relatively short distance from the explosion (<5 km: Figs. 4 and
270 11) and represents the short-period component of the wave spectrum. Wavelet analysis shows
271 that these short periods tend to disappear within 10-12 minutes after the explosion (Fig. 11).
272 As the distance from the explosion increases, the wave spectrum displays more complex
273 trends (Fig. 12). The intermediate-to-long periods predate the short periods, and the maximum
274 wave height is often reached several minutes after the arrival of the leading wave at the
275 shoreline.

276

277 **Implication for tsunami hazard evaluation**

278

279 The results of the numerical simulations presented above have important implications for
280 tsunami hazard evaluation in Taal Caldera Lake. First, there is only a short time available for
281 issuing a warning. All the subaqueous explosions generate tsunamis that propagate throughout
282 the lake in less than 10 minutes, while the nearest shorelines (e.g. coasts of Taal Island) are
283 impacted in less than 2 minutes. Thus, tsunami propagation is too fast to initiate evacuation at
284 the time of explosion. An exclusion zone should be set up prior to, or at the onset of, a
285 sublacustrine eruption. The efficiency of a tsunami warning system in Taal Lake partly relies
286 on monitoring techniques that would detect evidence of volcanic reawakening in the lake (e.g.
287 increased degassing leading to bubbles or jacuzzi, smoke at the surface of the lake, or changes
288 in water colour) as early as possible.

289 Secondly, a single tsunami event in the lake can have a very long duration. The effect of wave
290 resonance in the two basins can last several hours, thus prolonging the mechanical impact of
291 waves on anchored boats, harbours and fish-farming infrastructure. Repeated tsunamis during
292 a sublacustrine eruption would also cause severe coastal erosion. Sediments mobilised by the
293 waves at the lake bottom and those entrained offshore by the tsunami backwash would
294 threaten fish-farming activities.

295 Modelling tsunami waves breaking, interaction with coastal structures, and inundation inland
296 is beyond the scope of this paper, because it would require high-resolution elevation models
297 (typically 1 m grid resolution) and 3D models based on the Navier-Stokes equations.
298 However, as a first approach we have estimated wave heights at the shoreline for different
299 scenarios of subaqueous explosions. It is difficult to assign a probability to each of the
300 scenarios simulated. Observations of tsunami waves during historical eruptions do not provide
301 many constraints on wave heights and inundation distances. We know that waves inundated
302 the southwestern shore of the lake up to 17 m inland during the 1716 sublacustrine eruption

303 (Maso and Saderra, 1904). Also that wave runup reached 4.7 m above the level of the lake
304 during the 1965 eruption, even though the cause of the tsunami itself is debated (Moore et al.,
305 1966).

306 The size of the craters observed on Taal Island gives a rough estimate of the range of energies
307 delivered by the most powerful explosions (Eq. 2; Sato and Taniguchi, 1997). Craters have
308 diameters between 90 and 1700 m (central crater), but the majority of them are between 200
309 and 500 m, corresponding to explosion energies $3.5 \times 10^{13} \leq E \leq 5.6 \times 10^{14}$ J and initial surface
310 displacement $\eta_0 \leq 100$ m (Eq. 1; Le Méhauté and Wang, 1996). These source parameters can
311 be considered as the most probable scenario of tsunamis generated by an explosion in Taal
312 Caldera Lake. It is also consistent with the range of energies produced by phreatomagmatic
313 explosions (3×10^9 to 3×10^{14} J after Valentine et al., 2014).

314 Note that constant c in Eq. 1 is an important parameter as it depends on explosion depth d vs.
315 energy E . As an example, for explosions with a diameter of 500 m, the critical water depth is
316 50 m: below a depth of 50 m, explosions generate an initial surface displacement $\eta_0 = 100$ m,
317 whereas above 50 m water depth $\eta_0 = 50$ m. For $\eta_0 \leq 50$ m, wave heights at the shoreline are
318 less than 2 m with the non-dispersive model, and less than 0.5 m with the dispersive model,
319 whatever the explosion depth and location. Increasing the value of η_0 at 80 m or $110 \leq \eta_0 \leq$
320 130 m for very shallow explosions (depending on the constant c) yields wave heights up to 4
321 m (with the non-dispersive model) and 2 m (dispersive model) at a distance of ~ 5 km from the
322 explosion site. Worst-case scenarios of explosions with $\eta_0 \gg 100$ m generate wave heights
323 higher than 2 m all around the lake and locally higher than 10 m. However, the occurrence of
324 such large explosions outside the main crater is not supported by available historical or
325 geological observations, so it is uncertain whether such events are plausible.

326

327 **Concluding remarks**

328

329 Taal is one of the most active volcanoes in the Philippines and Southeast Asia, and its
330 proximity to human activities makes it challenging in terms of risk mitigation. Most of the
331 historical eruptions occurred in the central crater (e.g. 1749, 1754 and 1911 eruptions), but
332 sublacustrine activity is evidenced by the 1716 eruption and numerous emerged volcanic
333 cones around Taal Island. We simulated different scenarios of subaqueous explosions and
334 related tsunamis. This study has implications for tsunami hazard and risk evaluation in Taal
335 Caldera Lake. The dataset includes maps of tsunami propagation, time, and water surface
336 elevation, together with wave heights at the shoreline for 12 different coastal sites (virtual tide
337 gauge stations). These sites were chosen to represent crucial areas at risk from a tsunami.
338 Among all the activities distributed around the lake, schools, churches, coastal resorts (e.g.
339 northern coast), markets, fire stations, city halls (e.g. San Nicolas), the Taal Volcano
340 Observatory (east of Talisay), and fish-farming activities are the main vulnerable elements.
341 In this study, we only consider explosions occurring at an optimal depth for generating
342 tsunamis, i.e. explosions at the rim of the crater. However, tsunami generation is also
343 influenced by the evolution of the crater geometry during the eruption (crater excavation,
344 growth of the ejecta ring) and location of the explosion inside the crater, but these
345 relationships have not been tested experimentally or numerically. Horizontal and vertical
346 migrations of the successive explosions and their consequences in terms of tsunami
347 generation are quite unpredictable. More investigations are needed to understand why a
348 minority of subaqueous volcanic eruptions are tsunamigenic or evolve into conditions that can
349 generate tsunamis (e.g. decrease in the explosion depth).

350

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356

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358

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457

458

459 **Figure captions**

460

461 **Fig. 1** Volcanic hazards zonation in Taal Caldera Lake (based on hazard maps provided by
462 the Philippine Institute of Volcanology and Seismology - PHIVOLCS), and tsunamis
463 observed during historical eruptions. Subaqueous volcanic explosions and related tsunamis
464 are numerically simulated at several explosion sites and the wave heights are calculated at 12
465 virtual tide gauge stations around the lakeshore.

466

467 **Fig. 2** Physical parameters controlling the initial displacement of the water surface and
468 subsequent tsunami in the case of a subaqueous volcanic explosion. E: explosion energy; d:
469 explosion depth; D: total water depth around the volcanic cone; R: crater radius; η_0 : initial
470 water surface displacement.

471

472 **Fig. 3** Simulations of tide gauge records of tsunamis generated by two different subaqueous
473 explosions (scenarios 3 and 14 in Table 1), using a non-dispersive (COMCOT) and a
474 dispersive model of tsunami propagation (FUNWAVE-TVD).

475

476 **Fig. 4** Simulations of tide gauge records of tsunamis generated by an explosion at a water
477 depth of 50 m for three different values of initial surface displacement (η_0) corresponding to
478 three different explosion energies (scenarios 19, 20 and 21 in Table 1).

479

480 **Fig. 5** Tsunami wave arrival times following subaqueous explosions in the northern (A) and
481 southern (B) basins of Taal Caldera Lake. White stars indicate the explosion sites.

482

483 **Fig. 6** Initial surface displacement (η_0) vs. maximum tsunami wave heights (H_{\max}) calculated
484 at four different virtual tide gauges (see Fig. 1 for location) for different scenarios of
485 explosions in the northern (A) and southern (B) basins of the Taal Caldera Lake.

486

487 **Fig. 7** Maximum tsunami wave heights (H_{\max}) calculated at 12 virtual tide gauge stations
488 around Taal Caldera Lake for a subaqueous volcanic explosion in the southern basin
489 (scenarios 2 and 3 in Table 1). Histograms represent the results obtained with two values of
490 initial surface displacement (η_0) both for the non-dispersive and dispersive model of tsunami
491 propagation.

492

493 **Fig. 8** Maximum tsunami wave heights (H_{\max}) calculated at 12 virtual tide gauge stations
494 around Taal Caldera Lake for a subaqueous volcanic explosion in the northern basin
495 (scenarios 14 and 15 in Table 1). Histograms represent the results obtained with two values of
496 initial surface displacement (η_0) both for the non-dispersive and dispersive model of tsunami
497 propagation.

498

499 **Fig. 9** Maximum tsunami wave height (H_{\max}) vs. distance from the explosion. Two scenarios
500 of explosions are considered: a first explosion with $\eta_0 = 80$ m in the southern basin and a
501 second explosion with $\eta_0 = 140$ m in the northern basin.

502

503 **Fig. 10** Initial surface displacement (η_0) vs. maximum tsunami wave height (H_{\max}) at six
504 different tide gauges for an explosion close to the 1716 eruptive vent (sublacustrine eruption
505 in the southern basin). Six different values of η_0 are tested.

506

507 **Fig. 11** Spectral analysis of wave height vs. time at a virtual tide gauge station located in the
508 northern basin (Laurel) for an explosion at 105 m water depth in the northern basin ($\eta_0 = 120$
509 m) (scenario 11 in Table 1). A: wave height vs. time profile calculated at the Laurel virtual
510 tide gauge; B: wavelet power spectrum (continuous wavelet transform); C: frequency
511 spectrum (Lomb periodogram).

512

513 **Fig. 12** Spectral analysis of wave height vs. time at a virtual tide gauge station located in the
514 southern basin (Balete) for an explosion at 105 m water depth in the northern basin ($\eta_0 = 120$
515 m) (scenario 11 in Table 1). A: wave height vs. time profile calculated at the Laurel virtual
516 tide gauge; B: wavelet power spectrum (continuous wavelet transform); C: frequency
517 spectrum (Lomb periodogram).