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# Probabilistic hazard analysis for tsunamis generated by subaqueous volcanic explosions in the Campi Flegrei caldera, Italy

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13

# 14 Abstract

15 A probabilistic hazard analysis of tsunami generated by subaqueous volcanic explosion is 16 applied to the Campi Flegrei caldera (Campania, Italy). An event tree is developed to quantify 17 the tsunami hazard due to the submarine explosions by: i) defining potential size classes of 18 explosion magnitude on the basis of past volcanic activity in the Campi Flegrei caldera and 19 sites in the underwater part of the caldera; *ii*) simulating the generation and propagation of the 20 consequent tsunami waves able to reach the coasts of the Campania region for all 21 combinations of tsunami-generating vents and sizes; and *iii*) quantifying the tsunami 22 probability and relative uncertainty, conditional upon the occurrence of an underwater 23 eruption at Campi Flegrei. Tsunami hazard generated by subaqueous volcanic explosions is 24 considered crucial because of its potential high impact on the densely populated coastal areas of the Pozzuoli Bay and Gulf of Naples even if the probability for eruptions in the submarine 25 26 part of the caldera is certainly low. The tsunami hazard analysis is presented using conditional 27 hazard curves and maps, that is calculating the probability (and relative uncertainties) of 28 exceeding given tsunami intensity thresholds (wave amplitudes at the coast), given the 29 occurrence of a subaqueous eruption. The results indicate that a significant tsunami hazard 30 exists in many areas of the Bay of Naples.

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32 Keywords: volcanic tsunami, submarine volcanic explosions, caldera volcano, Campi Flegrei caldera

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#### 34

# 35 **1. Introduction**

36

Tsunamis generated by eruptive and gravitational processes on the flanks of volcanic edifices are quite infrequent (about 5% of all recorded tsunamis: Latter, 1981), but they represent the third cause of fatalities due to volcanism, with four tsunamigenic eruptions being ranked in the twenty deadliest volcanic disasters (e.g. Auker et al., 2013). Tsunami hazards related to subaqueous eruptions are particularly challenging to evaluate and forecast, due to a lack of geological, observational and instrumental data, in particular in densely populated regions such as the Campi Flegrei caldera in Italy (Fig. 1).

44 Different tsunami source mechanisms can be involved during a subaqueous eruption: pyroclastic flows, debris flows, caldera collapses and explosions (Paris, 2015). Tsunami 45 46 generation by subaqueous volcanic explosions is controlled by a range of physical parameters 47 including water depth, size of eruptive vent, energy and depth of explosion, and complex 48 magma-water interactions which determine the explosion itself (Le Méhauté, 1971; Kokelaar, 49 1986; Wohletz, 1986; Mirchina & Pelinovsky, 1988; Duffy, 1992; Le Méhauté & Wang, 1996; 50 Kedrinskii, 2005; Egorov, 2007; Morrissey et al., 2010). The explosion forms an initial crater-51 like cavity at the water surface (Fig. 2a), with a cylindrical bore that expands radially to form 52 the leading wave, followed by a wave trough. Initial surface displacement of the water surface 53 (i.e. maximum height of the bore) can be empirically estimated directly as a function of 54 explosion energy at a given water depth and size of the formed eruptive vent (Le Méhauté, 55 1971; Sato & Taniguchi, 1997; Goto et al., 2001). The initial downward displacement of the 56 water column (i.e. the cavity) is followed by an upward displacement, thus forming a steep 57 cone of water in the centre. This cone then collapses and turns to a second cylindrical bore, as 58 demonstrated by experimental explosions and numerical simulations (e.g. Le Méhauté & 59 Wang, 1996; Kedrinskii, 2005; Torsvik et al., 2010; Ulvrova et al., 2014 & 2016; Paris & 60 Ulvrova, 2019).

61 Different methods of Probabilistic Tsunami Hazard Analyses (PTHA) have been developed during the two last decades (Grezio et al., 2017). PTHA provides the likelihood of a given 62 parameter of the tsunami (e.g. wave height at the coast, flow velocity, flow depth, runup 63 64 height, or inundation distance) being exceeded at a particular location within a given period of 65 time. PTHA can combine geological, historical and instrumental data both of tsunamis (e.g. 66 sedimentary deposits, catalogues and historical accounts, tide-gauge records or pressure 67 sensor time-series), and of tsunami sources (source parameters, such as fault and seismicity 68 catalogue for earthquake sources), using statistical techniques and numerical simulations. Due 69 to the low relative frequency of tsunamis, concurring with the lack of repeated tsunami run-up 70 data spanning a long enough time period at a given location, the common practice is to 71 propose numerous different tsunami source scenarios with their associated probability (Geist 72 and Lynett, 2014). These scenarios are assumed to be a complete representation of the 73 expected natural variability (Selva et al., 2016). However, PTHA methods for landslide and 74 volcanic sources of tsunamis are far less established compared to the earthquake sources 75 (Grezio et al., 2017). Here, we produce a first attempt of considering volcanic sources. We 76 focus on conditional PTHA, that is, conditional upon the occurrence of a volcanic 77 phenomenon potentially generating a tsunami (i.e. submarine eruptions). The quantification of 78 long-term conditional hazard is common in volcanic hazard studies, since it allows for 79 planning evacuation in case of eruption (e.g. update of the National Emergency Plan for 80 Campi Flegrei, 2016: http://www.protezionecivile.gov.it/en/media-81 communication/dossier/detail/-/asset\_publisher/default/content/aggiornamento-del-piano-

82 nazionale-di-emergenza-per-i-campi-flegrei), as well as it provides reference simulations for 83 short-term hazard quantifications (e.g., Selva et al., 2014). Its extension to absolute PTHA 84 may be obtained by multiplying conditional hazard by the probability of occurrence of 85 volcanic eruption. With more than 20 eruptions in the last 5 ka (e.g. 25 eruptions listed by 86 Orsi et al., 2009), eruptions at Campi Flegrei have a mean annual rate on the order of  $10^{-3}$  per 87 year. However, we did not attempt here the estimation of any temporal component of the 88 hazard, which is not trivial being volcanic eruptive sequences clearly not stationary in time 89 (Bevilacqua et al., 2016).

In this study, we consider different scenarios of tsunamis generated by explosions in the offshore part of the Campi Flegrei caldera (Campania, Italy) and their effects on the coasts of the Pozzuoli Bay, the islands of Ischia and Capri, and the Gulf of Naples (Figs. 1 and 2a). These scenarios include different potential sizes and vent positions within the Campi Flegrei

94 caldera. They are then combined according to their probability of occurrence, quantifying the 95 consequent hazard in terms of conditional PTHA. The nested caldera of Campi Flegrei is a 96 complex partly submerged volcanic structure created mainly by multiple caldera forming 97 events: the 39 ka Campanian Ignimbrite, the 29 ka Masseria del Monte Tuff, and the 12 ka 98 Neapolitan Yellow Tuff (e.g. Deino et al., 2004; Marti et al., 2016; Albert et al., 2019). During 99 the last 12 ka, periods of high-frequency volcanism (mean intervals of 50-70 years) were 100 separated by periods of quiescence lasting from 1 to 3.5 ka (Di Vito et al., 1999). While the 101 onshore eruptive history of the caldera is well documented, past volcanic activity offshore and 102 the probability for future eruptions in the submarine part of the caldera (Pozzuoli Bay) have 103 been rarely discussed (Tonini et al., 2015; Selva et al. 2012a). Recent seismic and magnetic 104 surveys allowed the structural and magmatic evolution of the submerged southern half of the 105 caldera to be reconstructed (Aiello et al., 2012; Steinmann et al., 2018). The explosivity of 106 coastal-to-submarine eruptions such as Nisida Bank (~10 ka), Nisida Island (~4 ka), and Capo 107 Miseno (~3.7 ka) was recently reassessed to at least VEI 3 (Steinmann et al., 2018). Highly 108 permeable ring-faults along the southern rim of the caldera are prone to magma ascent 109 (Steinmann et al., 2018) and represent potential sites for future eruptions (Selva et al., 2012a). 110 Moreover, structural and geophysical data indicate the presence of several major faults in the submerged part of the caldera, representing potential weakness areas in which eruption may 111 112 be favoured (Selva et al., 2012a). Along these structures, the last eruption of Campi Flegrei 113 (Monte Nuovo, A.D. 1538) occurred starting at sea (Guidoboni and Ciuccarelli, 2011; Di Vito 114 et al. 2016).

115

### 116 **2. Methods**

117 The methodology presented in this paper is based on the development of an event tree (Newhall and Hobblit, 2002) for quantifying the tsunami hazard due to submarine explosions. 118 119 This method is based on 3 major steps: (1) the event tree was set by identifying 17 potential 120 vent areas in the underwater part of the Campi Flegrei caldera and 4 size classes of eruptive 121 events (three of which tsunami-generating explosive eruptions), allowing the definition of 122 17×3 representative tsunami-generating scenarios; (2) all the representative scenarios were 123 simulated, generating and propagating the consequent tsunami waves able to reach the coasts 124 of the Campania region; (3) the conditional probability of each representative scenario given 125 the occurrence of one eruption at sea was estimated, and combined with the corresponding

simulated tsunami scenarios, to produce the final conditional PTHA in the event-treeframework.

128

# 129 2.1. Setting the event tree to represent vent and size variability of eruptions

We considered here only those explosions deemed capable to generate tsunamis, i.e. eruptions occurring at sea with depth greater than 10 m. The adopted event tree for the Campi Flegrei caldera (Fig. 3) is the modified Bayesian Event Tree for Volcanic Hazard (BET\_VH) by Selva et al. (2010). Nodes 1-2-3 can be neglected, since probabilities are conditioned upon the occurrence of an eruption. Then, the residual event tree is composed only by 4 levels, which are relative to vent position, eruption size, and tsunami generation and intensity (nodes 4, 5, and 6-7-8, following Marzocchi et al. 2010).

At node 4 (vent position on Fig. 3), we reduced the original discretization from Selva et al. (2012a) in order to decrease the computational cost of the subsequent tsunami simulations, adopting a regular grid with cell size of  $1500 \times 1500$  m. Limiting only to the areas with not null conditional probability and water depth D > 10 m, we selected 17 equally spaced cells in the Pozzuoli Bay (Fig. 2b) as potential eruptive sites. Note that the explosion depth (*d*) used in the simulations is similar to water depth (*D*) and ranges between 23 and 111 m (Table 1).

143 At node 5, we adopted the four size classes for eruptions proposed by Orsi et al. (2009), in 144 line also with most of subsequent probabilistic volcanic hazard quantifications at Campi 145 Flegrei (Costa et al., 2009; Selva et al. 2010, 2014, 2018; Tonini et al. 2015, Sandri et al., 146 2016). Only 3 out of the size classes are relative to explosive eruptions. To characterize these 147 explosive classes in terms of tsunami-generation potential, we estimated the corresponding 148 crater dimensions using an analysis of the past activity in the caldera in three different epochs 149 of volcanic activity (Orsi et al., 2009). In epoch 1 (15-9.5 ka Before Present) 34 explosive 150 eruptions occurred, in epoch 2 (8.6-8.2 ka BP) 6 explosive eruptions and in epoch 3 (4.8-3.8 151 ka BP) 22 explosive and 3 effusive eruptions (di Vito et al., 1999; Orsi et al., 2009) (Fig. 2c 152 and 2d). On the basis of the correspondent crater characteristics, the explosive eruptions are 153 grouped in three size classes in terms of vent radius, corresponding to different explosive 154 energies. Thus, we selected 3 radius values (200, 650, and 900 m) as representative of the 155 three eruption classes. We assume that both submerged and emerged areas of the Campi 156 Flegrei undergo to similar explosive processes in the caldera.

157 At node 6, we considered only tsunamis generated by explosive eruptions. Of course, other 158 volcanic processes, such as flank collapses or pyroclastic density currents entering the sea, 159 may generate tsunami waves

160 At node 7-8 (Fig. 3), we adopted a "representative scenario" approach (Selva et al. 2010). In 161 this approach, each of the combinations of the 17 cells and 3 size classes is represented by a 162 single scenario with representative parameters (cell centre and representative radius), instead 163 of modelling the variability of both vent positions in each cell and crater sizes in each size 164 class (Sandri et al. 2016). In this way, the latter variability (intra-class) is assumed negligible 165 with respect to the inter-class variability (the one between the different representative vent 166 and size classes). Sandri et al. (2016) demonstrated that this approach is reasonable as first 167 order approximation for tephra fallout in the Probabilistic Volcanic Hazard Analysis (PVHA) 168 at both Somma-Vesuvius and Campi Flegrei, by quantifying the bias induced by adopting one 169 single representative scenario instead of sampling its natural variability. Given that we 170 adopted the same discretization for size classes, we assume that this can be extended to the 171 tsunami hazard. As a consequence, we defined 17×3 representative scenarios of explosions 172 with vent positioned in the geometrical centre of each of the 17 cells, and representative 173 radius of 200, 650, and 900 m for the three explosive classes.

174

## 175 2.2 Numerical simulations of explosion and tsunami

All the combinations of representative 17 vent locations and 3 vent sizes should be considered
as potential source for tsunamis. The energy of the explosion is estimated following the
empirical relationship given by Sato and Taniguchi (1997):

179  $E = 3.56 \times 10^7 R^3$  (Eq. 1)

180 where *E* is the explosion energy in Joules and *R* the radius of the eruptive vent in meters. 181 Following the method proposed by Torsvik et al. (2010) and Ulvrova et al. (2014, 2016), and 182 using the empirical formula of Le Méhauté and Wang (1996), the initial surface displacement 183 generated by the explosion is a parabolic cavity with a vertical steep water rim. The size of 184 the water cavity ( $R_c$ , in meters) is then estimated based on explosion energy using relationship 185 (Le Méhauté and Wang, 1996):

186 
$$R_c = 0.0361 E^{0.25}$$
 (Eq. 2)

187 The initial maximum vertical water surface displacement  $\eta_0$  of the cavity rim is also a 188 function of explosion energy at a given depth following:

189 
$$\eta_0 = c E^{0.24}$$
 (Eq. 3)

based on the empirical formula of Le Méhauté and Wang (1996, with  $\eta_0$  is in meters, and *c* is an empirical dimensional constant. According to the explosion yield and water depth, two cases are distinguished (Le Méhauté and Wang, 1996): (1) c = 0.0143 if  $6.15 \times 10^{-4} < d/E^{1/3} <$  $1.85 \times 10^{-2}$  (where d is the depth of explosion in metres); or (2) c = 0.0291 if  $d/E^{1/3} < 6.15 \times 10^{-4}$ . Values of explosion energy (*E*) and corresponding initial surface displacement ( $\eta_0$ ) of the 51 simulated scenarios are listed in Table 1.

196 All numerical simulations were performed using FUNWAVE-TVD code solving for the fully 197 non-linear Boussinesq-type wave equations in spherical coordinates (Kirby et al., 1998; Shi et 198 al., 2012; Tehranirad et al., 2013). Boussinesq model includes the effects of amplitude non-199 linearity and frequency dispersion in the case of intermediate-to-deep water waves (up to 200 wavelengths equivalent to water depth) although we neglect the effect of bottom friction. The third-order Runge-Kutta method is used to advance the model in time. An adaptive time step 201 202 is chosen following the Courant-Friedrichs-Lewy criterion. To ensure the stability of the 203 scheme, we set the Courant number to 0.5 and keep it constant for all simulations. Fourth-204 order spatial discretization is employed. We exploit only the maximum amplitude of the 205 incoming waves at the shoreline and neglect the inundation phase. We run the simulations for 206 25 minutes of the model time. In order to prevent reflections from the end-walls at the open 207 sea, we impose a 3 km wide sponge layer at the limit of the computational domain.

The spherical grid has a resolution of 39 m ×50 m (893×1595 grid nodes) in the longitudinal and latitudinal directions, respectively, covering about an area of 3000 km<sup>2</sup> between Ischia, Capri and Naples (Fig. 1). The grid was built by integrating printed nautical charts to digital elevation (Tarquini et al., 2007) and bathymetric models (D'Argenio et al., 2004) available for the study area. Typical water depth in the Gulf of Naples and Pozzuoli Bay ranges between 50 and 200 m. Wave heights at the coast were computed at >200 virtual tide gauge stations from Pozzuoli to Amalfi, including Ischia and Capri Islands.

215

216 2.3. Probabilistic hazard analysis

The probability at nodes 4 and 5 of the Event Tree are retrieved from literature. In particular, for node 4, we adopted the probability proposed by Selva et al. (2012a), cumulating the distribution parameters of the undersea (depth > 10 m) cells closer to our 17 selected vent positions. This probability distribution is not uniform, being eruptions in the centre of the gulf more probable due to the presence of main NE-SW trending fault system. At node 5, we adopted the distribution parameters of Orsi et al. (2009), as updated in Selva et al. (2018), with a decreasing probability for increasing explosion size.

- At node 6, we assume that effusive eruptions certainly do not produce tsunamis (conditional probability equal to 0 and no epistemic uncertainty), while explosive eruptions certainly produce tsunamis (conditional probability equal to 1).
- 227 At nodes 7-8, as tsunami intensity measure we selected the maximum wave amplitude (*Hmax*) 228 recorded at the coast (at a water depth of 1 m). Hazard curves were built at 421 target points 229 along the coast, from Cuma to Positano. To account for the rather rough discretization of the 230 aleatory distribution on source space (based on a broad grid for the vents and only 3 potential 231 sizes), as well as for the intrinsic uncertainty in the generation and propagation of the tsunami, 232 we introduced some level of uncertainty to the simulation results (Glimsdal et al., 2019). We 233 assumed that each scenario is associated to a conditional hazard curve (conditional upon a 234 scenario in that vent area and that size class) described by a log-normal distribution (see 235 Davies et al. 2017, and references therein). The parameters of the distribution ( $\mu$  and  $\sigma$ , mean 236 and standard deviation of the logarithmic values, respectively) were set based on simulation 237 results. Specifically, we set  $\mu$  as the average value of the log(*Hmax*), while a rather large 238 variance is assumed by setting  $\sigma = 1$  (slightly larger than the one adopted for earthquake 239 generated tsunamis in Davies et al. 2017). Given the first order approximation made by 240 defining in this way the log-normal distribution, we set to the obtained conditional hazard 241 curves the maximum allowed epistemic uncertainty (equivalent sample size equal to 1).
- 242
- **3. Results**

244

The three scenarios of explosions with vent radius, R, of 200, 650, and 900 m, correspond to 246 explosion energies, E, of  $2.9 \times 10^{14}$ ,  $9.8 \times 10^{15}$ , and  $2.6 \times 10^{16}$  J (Table 1). Following Eq. (3), 247 248 these explosions create an initial surface displacement of the water surface,  $\eta_0$ , of 85, 200, and 249 250 m, respectively (Table 1). Tsunami waves generated by the explosion propagate radially 250 away from the explosion centre, all over the computational area, with a significant influence 251 of the bathymetry (e.g. higher wave heights due to shallow banks around the Dohrn and 252 Magnaghi canyons in Fig. 4) and coastal morphology (e.g. effects of wave refraction around 253 the islands and capes in Fig. 4).

254 The highest tsunami impact is recorded on the coasts of the Pozzuoli Bay that are in the 255 imminent vicinity of the explosion centres. Maximum wave heights at the coast exceed 3 m 256 only in the Pozzuoli Bay and the eastern coast of Procida Island. Wave heights decrease by a 257 factor of 10 from the explosion site to the Gulf of Naples (note logarithmic scale of wave 258 heights on Fig. 4), where all sites record waves lower than 1.5 m for the scenarios with R =259 900 m and lower than 0.5 m for the scenarios with R = 650 m. As a result of wave refraction, 260 secondary peaks of wave heights are observed on the western coast of the Sorrento Peninsula 261 and eastern coast of Capri Island (i.e. at distances between 80 and 110 km on Fig. 5).

262 For a vent radius of 900 m ( $\eta_0 = 250$  m), wave heights higher than 10 m are restricted to the coasts of the Pozzuoli Bay (Figs. 4 and 5). Lowering vent radius to 650 m ( $\eta_0 = 200$  m) 263 264 reduces wave heights in the bay by a factor of 1.5 to 2 (Fig. 5). Wave height profiles recorded 265 at different tide gauge stations show that the scenarios with vent radius of 900 m generate 266 waves twice as high as the one with vent radius of 650 m (Fig. 6). Apart from this difference, 267 the two cases display the same wave patterns. Explosions corresponding to a vent radius of 268 200 m ( $\eta_0 = 85$  m) generate waves lower than 1 m high, even on the coasts of the Pozzuoli 269 Bay (Figs. 5 and 6), except at vent sites #16 and #17 (Fig. 2b) which are located near the 270 coast. In this case, waves locally reach amplitudes up to 2 meters (Fig. 5).

The propagation of the tsunami in the entire Gulf of Naples takes approximately 15 minutes. Waves reach Pozzuoli in 2 minutes, Procida in 4 minutes, Naples in 7 minutes, Capri in 9 minutes, and Castellamare di Stabia in 13 minutes (Fig. 6). The positive leading wave (peak) is the highest one, except for the stations located on the opposite side of the Gulf of Naples (e.g. Castellamare di Stabia, Capri). In the proximal field, the leading wave represents the short-period component of the wave spectrum (e.g. Pozzuoli, Procida, and Naples). As the distance from the explosion increases, the arrival of longer-period waves might predate the short-period waves because they travel faster in the Gulf of Naples. This is a direct effect of
frequency dispersion. At Castellamare di Stabia, the 0.7 m-high leading wave is followed by
higher waves progressively reaching a maximum height of 1.5 m (Fig. 6).

281

# 282 3.2. Probabilistic conditional hazard curves and maps

283 We produced tsunami hazard curves that are conditional to subaqueous eruptions, since only 284 eruptions with vent at sea are considered. Following Selva et al. (2018), the probability to 285 have a vent at sea (depth D > 10 m) given an eruption is approximately 0.11 (mean of the 286 epistemic uncertainty). Given one eruption, the probability of being an explosive one is about 287 0.89 (mean of the epistemic uncertainty). Therefore, the probability to have a tsunami-288 generating eruption conditional upon the occurrence of an eruption of any size in any vent at 289 Campi Flegrei is approximately equal to  $0.11 \times 0.89 = 0.10$  (again, mean of the epistemic 290 uncertainty).

291 The main results of the PTHA are presented as conditional hazard curves for each of the 421 292 target points along the coast, conditional upon the occurrence of an eruption at sea, and their 293 respective epistemic uncertainty. In Figure 7, we reported some example of conditional hazard 294 curves and hazard maps (mean of the epistemic uncertainty) corresponding to an exceedance 295 probability value of 0.05, either relative to one specific eruption size or integrating all 296 potential sizes. The value of 0.05 is chosen as a reference value as it is the same adopted for 297 the real planning in this area (e.g. update of the National Emergency Plan for Campi Flegrei, 298 2016). More specifically, in the top three panels we reported the hazard maps conditional 299 upon an explosive eruption at sea of size small (with representative radius R = 200 m), 300 medium (R = 650 m), and large (R = 900 m), respectively. In the bottom panel, we combined 301 all potential eruption sizes (including the non-tsunami-generating effusive size, in analogy 302 with Selva et al., 2008; 2018 and Sandri et al., 2016), reporting the conditional hazard map 303 given an eruption at sea for any size.

The results for the single eruptive classes show that the tsunami intensities may be significant in case of explosive eruption at sea, with intensities corresponding to 0.05 exceedance probability (mean of the epistemic uncertainty) always significant (> 1 m) inside the Pozzuoli bay, reaching tens of meters for medium and large explosive eruption classes (Fig. 7). In the case of medium and, even more, large explosive eruptions, significant intensities were found also in many areas of the larger Bay of Naples, with focalization point along the Sorrentopeninsula.

As observed for other hazards (e.g., tephra fallout in Sandri et al. 2016 and Selva et al. 2018), the hazard maps integrating all sizes provide results similar to the one conditioned to medium explosive eruption size, with slightly smaller intensity. Noteworthy, also integrating all potential sizes, eruptions at sea determine a significant tsunami hazard in many areas of the Bay of Naples, still with the largest potential intensities within the Pozzuoli Bay.

316

# 317 **4. Discussion**

318 Tsunami hazard related to subaqueous volcanic explosions in the study area, and particularly 319 in the Pozzuoli Bay, is far from negligible, even if the probability for eruptions in the 320 submarine part of the caldera is rather low. Considered largest scenarios of explosions (R=900321 m) generate waves higher than 10 m in the Pozzuoli Bay, but lower than 1.5 m in the Gulf of 322 Naples. Wave refraction creates local amplification (e.g. eastern coast of Capri) that is well 323 reproduced by the numerical models. The smallest explosions considered here (R=200 m) do 324 not represent a high hazard in terms of tsunami generation (waves < 1 m high). However, the 325 impact of such small tsunami waves should not be neglected on such densely populated 326 coasts. Another difficulty in terms of potential hazard mitigation actions comes from the 327 proximity of the tsunami source. The propagation of the tsunami in the entire Gulf of Naples 328 takes only 15 minutes. Pozzuoli is affected in less than 2 minutes.

In this work, tsunami wave behaviour at the coast (e.g. wave breaking, interaction with coastal structures) and inundation inland were not simulated, because it would require highresolution terrain models (typically 1 m grid resolution). In the near future, such simulations could be conducted at the local scale, i.e. on areas of specific interest (e.g. harbours), using those at the larger scale as input (Lorito et al., 2015; Volpe et al., 2019).

Another limitation comes from the model of explosion itself. We considered that the size of the crater reflects the most powerful explosion at shallow depth, regardless the total number of explosions (Goto et al., 2001; Taddeucci et al., 2010). In fact, the morphology of the crater might result from multiple vertically and horizontally-migrating explosions (e.g. Valentine et al., 2012; 2015). Thus, assuming that the size of the crater corresponds to the size of the explosion might lead to an overestimation of the explosion energy in some cases. We also assumed that the explosion occurs at the sea floor or at the rim of a pre-existing eruptive vent. However, the evolution of the vent geometry during the eruption (crater excavation, growth of the ejecta ring) and location of the explosion inside the vent might have an influence on tsunami generation. These relationships have never been tested experimentally or numerically.

345 Due to computational cost, we reduced exploration of aleatory variability such as vent 346 position and its size. This limitation was compensated by introducing a rather large 347 uncertainty into simulation results. However, given the illustrative character of this 348 application, we did not exploit any detailed analysis to better constrain the uncertainty 349 quantification. Temporal rates of eruptions are also difficult to constrain and, for this reason, 350 we did not extend our results to absolute unconditional probabilities, in line with previous 351 studies of this type (e.g. Sandri et al. 2016; Selva et al. 2018). However, we note that hazard 352 curves conditional upon eruption may represent a direct input for decision making. Indeed, 353 being possible short-term forecast of eruptions (e.g., Selva et al., 2012b), emergency plans are 354 usually based on such conditional hazard estimations (e.g. update of the National Emergency 355 Plan for Campi Flegrei, 2016). The probability of vents at sea is also poorly constrained.

Only few hazard analyses include the submerged part of Campi Flegrei as potential area for vent opening (Tonini et al., 2015). The presence of several major faults oriented NW-SE in the central part of the Pozzuoli Bay (see Orsi et al. 1994 and Selva et al. 2012a) tends to concentrate the probability of vent opening in this part of the submerged caldera. Ring-faults along the southern rim of the caldera also represent potential sites for future eruptions (Steinmann et al., 2018), but this has not been considered in this paper.

362 In this study, we considered only tsunami source generated by submarine volcanic explosions 363 at Campi Flegrei. However, other sources such as pyroclastic density currents entering the sea 364 or earthquakes and landslides should be integrated into the probabilistic analysis to avoid bias 365 in the tsunami hazard assessment (Grezio et al., 2015). For Campi Flegrei, submarine 366 explosions seem to be the dominating tsunami-generating volcanic process, given the topo-367 bathymetric configuration of the caldera and the prevalence in the past of dilute pyroclastic 368 density currents. However, other significant sources of volcanic tsunamis are present in the 369 Bay of Naples, including Ischia (Paparo and Tinti 2017 and reference therein) and Vesuvius 370 (Tinti et al. 2004). The Euro-Mediterranean Tsunami Catalogue (Maramai et al., 2014) 371 describes the sea withdrawals, sea retreats, and sea oscillations associated to volcanic activities and reports tsunamis with intensity 2 (meaning waves lower than 1 m), mainly
associated to pyroclastic density currents generated during explosive eruptions at Mt.
Vesuvius.

375

# **5.** Conclusion

377 The conditional probabilistic hazard assessment for tsunamis generated by subaqueous 378 volcanic explosions is presented for the Campi Flegrei caldera. The probability for eruptions 379 in the submarine part of the caldera is rather low, but scenarios of tsunamis generated by 380 subaqueous volcanic explosions and their potentially high impact in the Pozzuoli Bay and 381 Gulf of Naples deserve to be considered due to high population density of these coastal areas. 382 We demonstrated that tsunamis from volcanic explosions in the Campi Flegrei caldera 383 represent a significant source of hazard in the Pozzuoli Bay and Gulf of Naples. This is often 384 overlooked, but should be integrated into the evaluation of natural hazards of the area. 385 Highest hazard is found on the coasts of the Pozzuoli Bay, where incoming tsunami waves 386 exceeding locally 10 m can be expected in case of future large explosions. Around Naples, 387 where coasts are densely populated, the hazard is lower, but tsunamis exceeding 1 m are 388 assessed. In this study, we considered tsunamis generated by volcanic explosions only, but 389 other tsunamis sources such as earthquakes or landslides should be included in the future to 390 fully evaluate the hazard in the region. Future developments could be the evaluation of a 391 complete PTHA due to volcanic processes in the Campania region considering underwater 392 caldera explosions, landslides, and pyroclastic density currents both from Vesuvius and Campi 393 Flegrei eruptions.

394

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592

## 593 Figure captions

Fig. 1. Location map of the study area. The Pozzuoli Bay corresponds to the southern
emerged part of the Campi Flegrei caldera. Bathymetry by D'Argenio et al. (2004).

596 Fig. 2. A) Physical parameters controlling the initial displacement of the water surface and 597 subsequent tsunami in case of subaqueous volcanic explosion: E: explosion energy; d: 598 explosion depth; D: total water depth around the volcanic cone; R: eruptive vent radius; 599  $\eta_0$ : initial water surface displacement. B) Location of the 17 explosion sites tested for tsunami simulations in the Pozzuoli Bay. C) Craters of past eruptions at Campi Flegrei. 600 601 The size of the craters (circles) is used to determine the three classes of radii of eruptive 602 vents (modified from Costa et al. (2009). D) Dense Rock Equivalent versus Vent radius 603 showing the relationship between the erupted magma volume and the size of the vents.

Fig. 3. Bayesian Event Tree for Volcanic Hazard (BET\_VH) for the Campi Flegrei caldera
(modified from Selva et al., 2010) adopted in this study. In light grey, we report the
nodes that are not quantified, due to the choice of conditioning the probabilities upon
the occurrence of subaqueous explosions.

608Fig. 4. Maximum water elevation for explosions at site #1. Three cases of eruptive vent radius609are distinguished (200, 650, and 900 m), corresponding to explosion energies of610 $2.9 \times 10^{14}$ ,  $9.8 \times 10^{15}$ , and  $2.6 \times 10^{16}$  J, respectively (see Table 1). Blue colour corresponds611to water displacements inferior to 0.1 cm. Dark blue areas at the edges of the612computational domain represent a sponge layer that is prescribed at the grid boundaries613in order to dump incoming waves and hence prevent reflections to form at the end walls.

Fig. 5. Maximum wave amplitude recorded at the coast (*Hmax*) as a function of distance
along the coastline (starting from the NW) for 3 different explosion sites (#4, #7, and
#17). Cities of Pozzuoli, Naples, Torre del Greco, and Castellamare di Stabia are located
at distances of 20, 40, 50, and 65 km, respectively.

Fig. 6. Wave heights generated by underwater explosions at site #1 and recorded at the coast
at 7 virtual tide gauge stations. Three different values of vent radii (200, 650, and 900
m) are represented, corresponding to different energies of explosion.

Fig. 7. For each individual size class (rows 1 to 3) and their combinations (row 4), we report
the conditional mean hazard maps for a probability threshold = 0.05 (maps on the left)

and the conditional hazard curves (mean and 10<sup>th</sup>-90<sup>th</sup> percentiles confidence interval) in 623 624 one point (black square) within the city of Naples (red lines on the right). All hazards are conditional upon submarine explosive eruptions (SEE) of size 1 (top panel), size 2 625 626 (second top panel), size 3 (third top panel), and any size (bottom panel). Note that, for sizes 2 and 3 (medium and large vent radia), the hazard curves have probability 627 628 approaching 1 for relatively small tsunami intensity, meaning that the exceedance of 629 such intensity in that position approaches certainty in case of submarine eruptions of 630 these sizes.





























Vent radius - R = 900

a-Pozzuoli







Explosion site	long (°)	lat (°)	d (m)	R (m)	E (J)	$\eta_0(m)$
1	14.131004	40.76432	93	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
2	14.095464	40.764046	82	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
3	14.113234	40.764184	100	200	2.90E+14	85
				650	9.80E+15	200
4	14.09528	40.777558	28	900	2.60E+16	250
				200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
5	14.113054	40.777696	103	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
6	14.130828	40.777831	104	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
7	14.148602	40.777963	111	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
8	14.095097	40.791069	35	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
9	14.112875	40.791207	99	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
10	14.130652	40.791342	101	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
11	14.14843	40.791475	93	200	2.90E+14	85
				650	9.80E+15	200

**Table 1**. Scenarios of subaqueous volcanic explosions. d is explosion depth (similar to water depth in this case); R is radius of the eruptive vent; E is explosion energy;  $\eta_0$  is initial displacement of the water surface.

				900	2.60E+16	250
12	14.094914	40.80458	75	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
13	14.112695	40.804718	63	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
14	14.130476	40.804853	62	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
15	14.148257	40.804986	49	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
16	14.09473	40.818091	37	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250
17	14.112515	40.818229	23	200	2.90E+14	85
				650	9.80E+15	200
				900	2.60E+16	250