Nat. Hazards Earth Syst. Sci., 12, 151–163, 2012
www.nat-hazards-earth-syst-sci.net/12/151/2012/
doi:10.5194/nhess-12-151-2012

Natural Hazards and Earth System Sciences

Tsunami risk assessments in Messina, Sicily – Italy

A. Grezio[1], P. Gasparini[2,3], W. Marzocchi[4], A. Patera[4], and S. Tinti[5]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Via Creti 12, 40128 Bologna, Italy
[2]AMRA Scarl, Via Nuova Agnano 12, 80012 Naples, Italy
[3]Dipartimento di Scienze Fisiche, Università di Napoli, "Federico II", Naples, Italy
[4]Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy
[5]Dipartimento di Fisica, Settore di Geofisica, Università di Bologna, Bologna, Italy

Correspondence to: A. Grezio (grezio@bo.ingv.it)

Received: 14 April 2011 – Revised: 9 September 2011 – Accepted: 4 December 2011 – Published: 17 January 2012

Abstract. We present a first detailed tsunami risk assessment for the city of Messina where one of the most destructive tsunami inundations of the last centuries occurred in 1908. In the tsunami hazard evaluation, probabilities are calculated through a new general modular Bayesian tool for Probability Tsunami Hazard Assessment. The estimation of losses of persons and buildings takes into account data collected directly or supplied by: (i) the Italian National Institute of Statistics that provides information on the population, on buildings and on many relevant social aspects; (ii) the Italian National Territory Agency that provides updated economic values of the buildings on the basis of their typology (residential, commercial, industrial) and location (streets); and (iii) the Train and Port Authorities. For human beings, a factor of time exposition is introduced and calculated in terms of hours per day in different places (private and public) and in terms of seasons, considering that some factors like the number of tourists can vary by one order of magnitude from January to August. Since the tsunami risk is a function of the run-up levels along the coast, a variable tsunami risk zone is defined as the area along the Messina coast where tsunami inundations may occur.

1 Introduction

The 28 December 1908 Messina earthquake was one of the most destructive events in Italy and was associated with one of the largest tsunami inundations in recent history. About 60 000 people died because of the earthquake and about 1500 were killed by the tsunami. The cities of Messina and Reggio-Calabria were damaged extensively. The tsunami run-up was 3 m in the Messina harbour and as high as 13 m in the village of Pellaro, and the tsunami waves entered 200 m inland in several locations along the coast of the Messina Straits (Tinti et al., 1999). For the first time, a Tsunami Risk (TR) assessment for the city of Messina is presented, where the TR is evaluated considering the tsunami hazard, the vulnerability of the exposed elements and the value of such elements. Generally, TR assessment uses hazards provided by the worst expected scenarios based on historical data and/or on few simulations (Papadopoulos and Dermentzopoulos, 1998; Sato et al., 2003; Kulikov et al., 2005). Grezio et al. (2010a) point out the need of an extensive set of potential tsunamigenic sources with the appropriate evaluation of the aleatoric and epistemic uncertainties in order to consider a more comprehensive Probabilistic Tsunami Hazard Assessment (PTHA). As regards the estimation of damages, it is extremely difficult to establish levels of vulnerability of people and communities, because of the multiplicity of individual and social aspects (Dweyr et al., 2004). Recent studies have demonstrated that the vulnerability is a dynamic variable and depends on a number of parameters. As a consequence, buildings and spaces are not uniformly at risk within a potential inundation zone (Papatoma et al., 2003a, b). It is clear that time and spatial variability, involving multiple factors, make the TR assessment a complicated issue.

The main goal of the analysis we perform in this work is a TR quantification and mapping for the city of Messina, carried out as accurately as possible. Section 2 presents the methodology of the TR assessment and describes extensively the tsunami hazard, the exposed elements and the vulnerability; Sects. 3 and 4 report respectively the results of the Tsunami Damage (TD) and the Tsunami Risk (TR) both for human and building cases; Sect. 5 remarks on the main aspects discussed in the paper.

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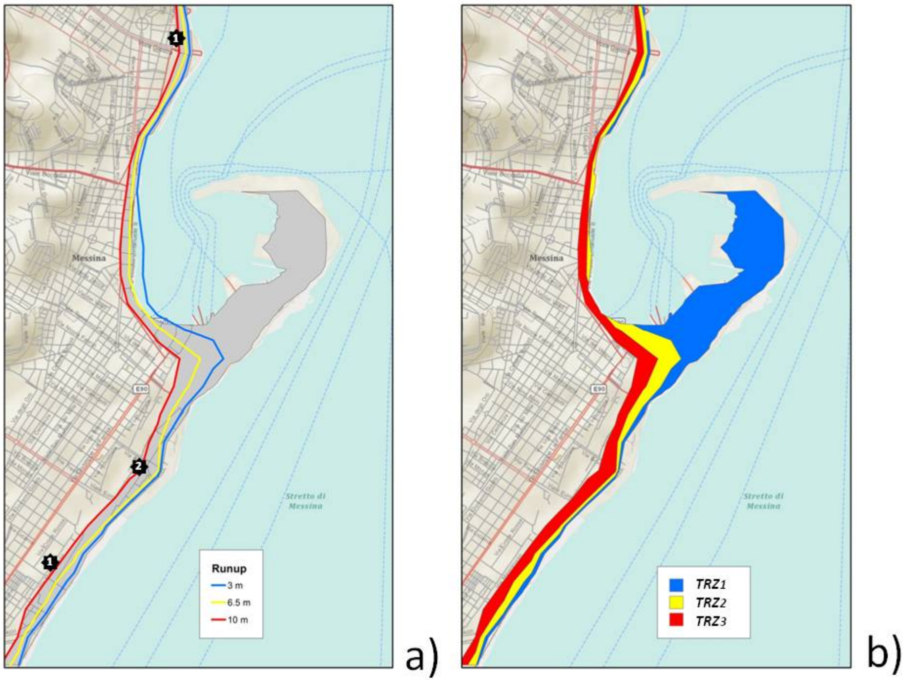


Fig. 1. Messina ISTAT sections on ArcGIS map: **(a)** the run-up isolines in Messina city (star symbols indicate the location of the corresponding number of buildings with 4 or more floors) and **(b)** the Tsunami Risk Zones TRZ_i $(i=1,2,3)$. The gray lines are the ISTAT section and the dark gray area in **(a)** (limited by 0.5 m and 10 m runup) is relative to the 54 sections of the TRZ.

2 Tsunami risk assessment methodology

The TR is based on the general definition of risk by Fournier D'Albe (1979):

$$\text{Risk} = (\text{Hazard}) \times (\text{Exposed Elements}) \times (\text{Vulnerability}) \quad (1)$$

where Hazard is the probability of any particular area being affected by a calamitous event within a given period of time; Exposed Elements is a generic term indicating the number of human lives at stake and/or the economic value of lands, buildings, infrastructures, or other productive facilities (factories, power plants, agricultural lands, tourist activities) which are exposed to that event; Vulnerability is the proportion of the exposed elements (in terms of human lives and/or economic values) which is likely to be lost in that event, and is therefore a number comprised between 0 and 1.

Here, we present TR assessment evaluated separately for Humans TR and Buildings TR. They are functions of the run-up levels along the coast, so that we define a Tsunami Risk Zone (TRZ) as the area along the Messina coast where a tsunami inundation may occur. In the present case, we focus on three TRZ_i $(i=1,2,3)$, considering the 0.5–3 m, 3–6.5 m, and 6.5–10 m run-up level intervals. The lowest limit 0.5 m and is the one set by the PTHA analysis (Grezio et al., 2010a); the 3 m value is the run-up level of the 1908 tsunami event in Messina; the 6.5 m value is arbitrarily chosen and the upper limit 10 m is an extrapolation case. TRZ_1 is the area limited by the run-up levels 0.5–3 m and is a strip about 35 m wide, on average with a total area of about $5.3 \times 10^5\,\mathrm{m}^2$ including the peninsula of the port of Messina. TRZ_2 is limited by the run-up levels 3–6.5 m and is a strip about 50 m wide with total area of about $2.3 \times 10^5\,\mathrm{m}^2$. TRZ_3 is limited by the run-up levels 6.5–10 m and is a strip about 60 m wide with total area of about $3.7 \times 10^5\,\mathrm{m}^2$.

The TR analysis carried out in each TRZ is made by subdividing the territory following the partition adopted by the Italian National Institute of Statistics (Istituto Nazionale di Statistica – ISTAT, http://www.istat.it/). ISTAT data are given in territorial units called sections and cover the whole Italian territory. ISTAT provides information on the population, buildings and many relevant social aspects of the Italian national territory according to the last Population Census in 2001. We asked ISTAT to extract the data relative to the city of Messina from the national database. The sections are portions of the city that represent the highest available resolution of a complete set of territorial information. In Messina there are almost 1600 sections, but for the TR assessment we have selected only the sections which may be inundated by the potential tsunami in the ranges limited by the 0.5–10 m run-ups and they are 54. Figure 1 reports on an ArcGIS map: (a) the 0.5 m, 3 m, 6.5 m and 10 m run-up isolines that are based on a topography-bathymetry dataset with 200 m resolution and (b) the TRZ_i $(i=1,2,3)$ limited by the run-ups.

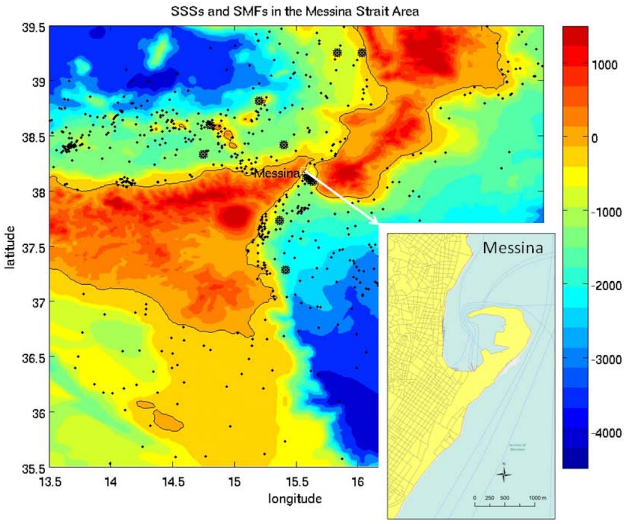


Fig. 2. The Messina Strait Area. Submarine Seismic Sources (SSSs) are the black dots and Submarine Mass Failures (SMFs) are the black stars. The map of the city of Messina with the all ISTAT sections is shown in the lower box.

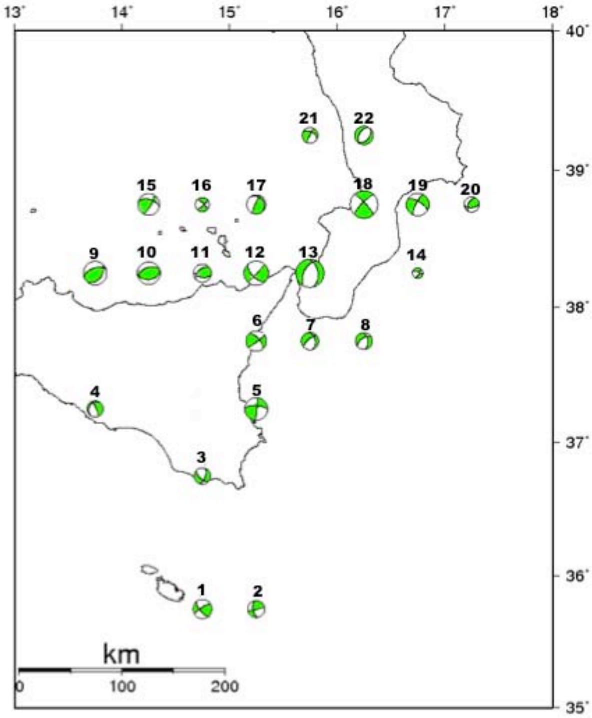
2.1 Probabilistic Tsunami Hazard Assessment (PTHA)

In the present study, the tsunami hazard is computed from an extensive set of potential tsunamigenic sources with the relative aleatoric and epistemic uncertainties formally incorporated. Note that this approach is different from other procedures that consider only few seismic sources and scenarios. According to the Bayesian PTHA (Grezio et al., 2010a) and the relative application to the Messina Strait Area (Grezio et al., 2010b), the hazard is calculated as the annual probability that a tsunami run-up Z overcomes a selected threshold z_t at the Messina coast. The procedure uses all information available for Messina: regional seismotectonics background, empirical models, recent instrumental data, historical catalogues. In this TR assessment, the Submarine Seismic Sources (SSSs) and Submarine Mass Failures (SMFs) are considered as the predominant tsunamigenic sources.

SSSs are localized on active faults around the Sicily region at depths smaller than 15 km within the shallow part of the crust. The epicenters are extracted from the instrumental Catalogue of the Italian Seismicity that contains earthquakes with a completeness magnitude of 2.5 (Castello et al., 2007). Figure 2 shows the SSSs locations recorded from 1981 to 2002 in the northern and eastern Sicily, that is called the Messina Strait Area. Since all instrumental magnitudes in such a short time span happened to be below the threshold to trigger a tsunami, virtual magnitudes in the range [5.5–7.5] M_w are associated with the catalogue locations. Specifically, we assume first that large earthquakes have the same spatial distribution of the smaller ones and second that they follow a Gutenberg-Richter frequency-magnitude relationship (Gutenberg and Richter, 1944). Note that the introduction of those magnitudes is necessary in order to make the SSSs potentially tsunamigenic. Other fault parameters (width, length and slip) related to these SSSs magnitudes are calculated using the empirical relationships provided by Wells and Coppersmith (1994). Source depths are randomly distributed in the upper 15 km of the crust. Focal mechanisms are selected according to the Earthquake Mechanisms of the Mediterranean Area database (Vannucci and Gasperini, 2004) and following the Harvard Central Moment Tensors procedures in the Mediterranean region (Pondrelli et al., 2004) (Fig. 3). Strike, dip and rake angles are selected taking into account the regional seismotectonics consistently with the background studies and are listed in Fig. 3. Sea floor deformations induced by the SSSs are calculated via the Okada (1992) analytical formulas in order to compute the initial tsunami sea surface heights.

SMFs are associated to areas with propensity to failure that are specified considering the bathymetry slopes and the mass centre depths in the Messina Strait Area (Fig. 2). SMFs volumes span from 5×10^5 to 5×10^{10} m^3 on the basis of regional and historical SMF sizes measured in the Tyrrhenian and Ionian basins. Other geometric parameters are calculated using the rigid body approximations following Grilli and Watts (2005) and Watts et al. (2005). In analogy with the sub-aerial mass failures, the frequency distribution of the SMFs is assumed to be a power-law distribution and posterior spatial conditional probabilities are introduced considering past SMF scars that represent instability areas. The initial tsunami sea surface amplitudes are computed following Grilli and Watts (2005) and Watts et al. (2005), who stated that it is reasonable to use the sea surface amplitudes formulas as first approximation in the tsunami hazard along any given slope. Finally, the surface elevations of the initial tsunami waves are approximated using the surface amplitudes (in the near field and away from the splash zone).

The initial tsunami waves are propagated by an empirical amplification law (Synolakis, 1987) that is considered the prior model in the Bayesian PTHA. The use of the empirical law was necessary in order to simulate a great number of potentially tsunamigenic events in a reasonable computational time and in order to explore the aleatory uncertainties of the random nature of the tsunamigenic sources. This approach implies that the final PTHA is computed at the first order approximation because of the limitations of the Synolakis' law in the run-up calculations. In fact, the empirical formulation is intrinsically not able to reproduce important processes of a tsunami event like the refraction and diffraction effects during the wave propagation near to the coast and the non-linearity of the wave dispersion and wave breaking. Hence, further study with even a simple non-linear numerical model is recommended where location and geometrical morphology of the coast may result particularly relevant in the simulation of the tsunami wave approaching the coast. However, in order to assess a first order PTHA as it was tested by Grezio et al. (2010a) for the Sumatra-Andaman 2004 event,



N	Strike	Dip	Rake
1	140	67	164
2	76	86	146
3	20	60	- 35
4	335	80	- 110
5	7	85	26
6	52	83	28
7	347	38	- 145
8	353	49	- 137
9	38	41	64
10	82	43	99
11	98	50	127
12	135	60	- 176
13	208	55	- 65
14	30	67	- 160
15	30	75	- 138
16	48	76	- 163
17	203	80	109
18	224	77	169
19	302	68	- 165
20	208	51	47
21	297	51	- 178
22	43	43	- 80

Fig. 3. Moment Tensors and correspondent Strike, Dip and Rake angles in the Messina Strait Area listed in the relative Table.

we computed an extensive set of run-ups Z using the continental slope angle of an average slope computed in a reasonable area in front of Messina city.

The run-ups $Z > z_{\mathrm{t}}$ at the Messina coast computed by Synolakis' law are used to set the Beta distribution with parameters α and β in the prior probability distribution $f_{\mathrm{prior}}(\theta)$ of the Bayesian PTHA (Grezio et al., 2010a):

$$f_{\mathrm{prior}}(\theta) = \mathrm{Beta}(\alpha,\beta) = \frac{1}{B(\alpha,\beta)}\theta^{\alpha-1}(1-\theta)^{\beta-1}, \quad 0<\theta<1 \tag{2}$$

where

$$B(\alpha,\beta) = \int_0^1 x^{\alpha-1}(1-x)^{\beta-1}dx, \alpha>0, \beta>0 \tag{3}$$

is the Beta function. The α and β parameters are univocally determined in practical tsunami applications by the expected value E and the variance V. The value E is set equal to the weighted percentage of times in which $Z > z_{ti}$ in a statistically relevant number of computed run-ups from the N different simulated tsunamigenic sources. In the present application z_{ti} assumes the different run-up thresholds $z_{t1} = 0.5\,\mathrm{m}$, $z_{t2} = 3\,\mathrm{m}$, $z_{t3} = 6.5\,\mathrm{m}$, and $z_{t4} = 10\,\mathrm{m}$. So that:

$$E(\theta) = \sum_{j=1}^{N} p_j H(Z_j > z_{t_i}) \quad i = 1,...4. \tag{4}$$

$H(Z_i - 0.5\,\mathrm{m})$ is the Heaviside step function that is 1 when the simulated run-up Z_i from the simulated i-th tsunamigenic source is larger than the thresholds z_{ti} and 0 otherwise, and p_i is the probability of occurrence of the i-th tsunamigenic source in a time window that was set equal 1 yr. The variance V is calculated by

$$V = E(1-E)/(\Lambda+2) \tag{5}$$

where Λ is the reliability parameter which is set equal to 10 in the tsunami case. The Λ parameter is considered the assigned reliability of the prior model (Marzocchi et al., 2008), meaning that more than 10 historical data can change the prior probability distribution significantly (Grezio et al., 2010a). Following the definitions in Marzocchi et al. (2008), E and V can be expressed by

$$E = \alpha/(\alpha+\beta) \text{ and } V = E(1-E)/(\alpha+\beta-1) \tag{6}$$

Having calculated E by Eq. (4) and V by Eq. (5) and inverting for α and β in Eq. (6) the prior distribution $f_{\mathrm{prior}}(\theta)$ is univocally defined by those parameters.

The Bayesian procedure provides the posterior probability distribution that integrates the prior probability distribution (based on the physical knowledge of the process and instrumental information) and the likelihood (based on the historical data in Messina). Those historical data are extracted by the catalogue of the Italian Tsunami (Tinti et al., 2004) and other studies (full details in Grezio et al., 2010b) where the

Table 1. Mean of the posterior probability $\times$ yr^{-1} in the TRZ$_i$ ($i = 1,2,3$).

	TRZ$_1$	TRZ$_2$	TRZ$_3$
II	5.9×10^{-3}	3.9×10^{-3}	0.0003×10^{-3}

tsunami intensity and the relative run-ups are indicated for tsunami events that occurred in the last 500 yr. For large run-up thresholds ($z_{ti}, i = 2,3,4$), the historical information in the catalogue of the Italian Tsunami are exhaustive because of the importance of the events. Small tsunami waves with intensity <3 usually meaning run-up <1 m and/or 0.5 m run-ups were not reported by the past observations in Messina. However, Papadopoulos (2009) showed the correlation between earthquake magnitude and tsunami intensity expressed by the Sieberg-Ambraseys scale. In the magnitude range of the present study, it is possible to individuate 11 events of tsunami intensity ≥2 in the Mediterranean Sea based on Papadopoulos' (2009) study. Considering this general figure representative also for the Messina Strait Area, we conjecture that the annual probability of tsunami overcoming 0.5 m would be higher in TRZ$_1$.

Finally, in the present study we calculated the annual posterior probability $f_{\text{post}}(\theta)$ by the Beta distribution

$$f_{\text{post}}(\theta) = \text{Beta}(\alpha + y, \beta + n - y) \tag{7}$$

where y and n are respectively the number of events and the number of success. In general, if $f_{\text{post}}(\theta)$ defines the probability of occurrence of at least one tsunami event, then 1-$f(\theta)$ is the generic probability that no tsunami occurs. The final posterior distribution $f_{\text{post}}(\theta_{\text{final}})$ that combines both SSSs and SMFs cases in the Messina Strait Area is then

$$f_{\text{post}}(\theta_{\text{final}}) = 1 - [(1 - f_{\text{post}}(\theta_{\text{SSS}}))(1 - f_{\text{post}}(\theta_{\text{SMF}}))] \tag{8}$$

Specifically for this tsunami application, we calculated the mean of the annual posterior probability (Π) that is associated to each TRZ$_i$ ($i = 1,2,3$) (Table 1). Further details on the General Modular Bayesian PTHA procedure and its application in the Messina area can be found in Grezio et al. (2010a, b).

2.2 Exposed Elements (EE)

The exposed elements (humans and buildings) represent the elements that can be lost in the TRZ during a calamitous tsunami.

2.2.1 Human Exposure (HE)

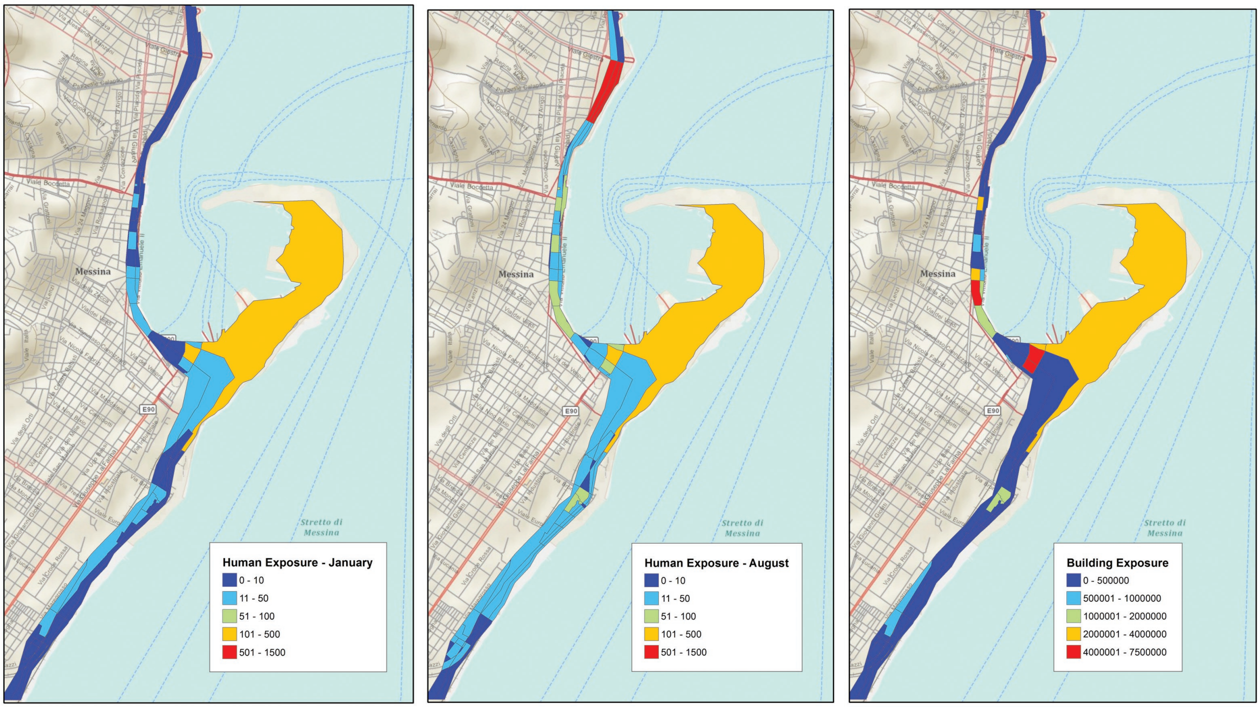
In the HE case, a factor indicating the time of exposition (T_{EXP}) to a potential tsunami event is introduced. This factor is expressed in terms of hours, h, per day (h/24): it is not constant during the year in private and public places and it also changes from one category to the other. For example, the number of tourists and students varies by at least one order of magnitude from winter to summer. Two months (January and August) are chosen to describe the minimum and maximum HE during a representative year. The HE was estimated in different places both private and public. The private places are grouped into the following categories: Residential Houses, Hotels and B&Bs. The public places are grouped in: Schools (nursery school and day nursery, primary, secondary, and high schools, both public and private schools) and Universities; Hospitals and Emergencies; Trade Fair; Port and Train Station. Workers are almost a constant number during the year, generally with about 2 work shifts of about 8 h each. Students, patients, tourists, and visitors are in variable number during each month and during the day. For the HE estimations, we use the highest number of people present in the TRZ for the longest time. It means that the worst case of exposure to a potential tsunami is considered.

- The total number of Residents in the TRZ is about 788. Their T_{EXP} is 1 (= 24/24); this assumption means that all the residents could be present in the TRZ at any time during the year. These data have been extracted from the ISTAT 2001 census.

- The number of Tourists in Messina in January is about 209 per day and in August about 2299; this is a number based on the available tourist accommodation in Hotels, B&Bs and campings in the city area. Since it is difficult to locate the tourists, we consider them uniformly spread over the TRZ. In general we assume that their T_{EXP} is 1 (= 24/24), as it is for the residents. Information on tourists arriving in Messina is provided by ISTAT 2006 (Pontrelli, 2007; Tinti et al., 2008).

- A High School and a University Office are present in the TRZ$_3$. On average there are about 30 PhD students during the day in January and just about 10 students per day in August and 10 employees in the University Office. In the High School edifice there are 560 students, 120 professors and 25 more workers. The assigned T_{EXP} is 0.25 (= 6/24) for the high school in January and 0 in August, when schools are closed. The T_{EXP} for the people in the University Office is 0.333 (= 8/24). These data have been provided respectively by the Headmaster of the High School and by the overseer of the PhD Office of the University for the school/academic year 2008–2009.

- The number of trade fair visitors is about 300 in the most important exposition in January and it can even reach the total number of 300 000 people in August (personal communication by the personnel) for the most important event in summer. Their T_{EXP} factor is equal 0.333 (= 8/24) in January and 0.50 (= 12/24) in August. Information are provided by the Trade Fair Office.



(a) (b) (c)

Fig. 4. Human Exposure HE_i^j in terms of number of persons **(a)** in January and **(b)** in August, and **(c)** Building Exposure BE_i^j in terms of economic value (Euro) in each j-th section fraction in the i-th TRZ_i ($j = 1, 54$ and $i = 1, 2, 3$).

– There are no hospitals and emergencies in the TRZ. However, since we suggest a general procedure, it is worth suggesting how to treat this category of structures. We separate the T_{EXP} of hospitals from the T_{EXP} of emergencies. They are different and are respectively 1 (= 24/24) for patients in hospitals, and 0.333 (= 8/24) for working people like doctors, nurses, and so on, with 3 work shifts. The T_{EXP} in emergency is 0.083 (= 2/24) for patients, a value calculated as an average waiting time in Messina, and 0.333 (= 8/24) for working people.

– The total number of travelling people in the Messina Train Station is 4798 in winter and 4381 in summer during a typical working day and it is 937 in winter and 1060 in summer during a holiday. Due to the location of the railway station, we assume that travellers are distributed between TRZ_1 and TRZ_2. We choose the highest number in both cases (January and August) without distinction between working days and holidays and assume a mean waiting time of half an hour in the train station, T_{EXP} 0.021 (= 0.5/24). There is no available information about the staff. Data are provided by the Train Authorities.

– The total number of travelling people in the Messina Port is about 1203 per day and the number of working people is 501. All these people are attributed to the TRZ_1. The usual time of staying in the port before crossing the Messina Strait is about 1 h, then the T_{EXP} of the travellers is 0.042 (= 1/24). The working time exposition factor is equal 0.333 (= 8/24) because 8 h is a working shift, assuming 2 shifts per day with suspended work in the night. Data are provided by the Port Authorities (Pontrelli, 2007; Tinti et al., 2008).

All these data are summarized in Table 2. According to the above data, the total daily HE in January is 1084 and in August, 5304. These results represent the lowest and the highest number of people exposed daily to a potential tsunami wave in Messina in the area limited by the run-up levels 0.5–10 m in two significant periods of a generic year.

The ISTAT sections are used to estimate the HE in a higher resolution representation of the Messina territory. Section extension and data are very different and heterogeneous in each TRZ_i ($i = 1, 2, 3$). We also consider that each section and the relative data are not completely included in a single TRZ but can be divided by the runups isolines in two or more portions pertaining to different TRZs. First, we evaluate the mean areal density A_i of the daily HE_i in each i-th zone

$$A_i = \mathrm{HE}_i / S_{Ai}, \qquad i = 1, 2, 3 \tag{9}$$

where HE_i indicates the number of exposed people that can be found on average in the TRZ_i with area S_{Ai}. The HE_i for

Table 2. Daily HE in the TRZ_i ($i = 1,2,3$) in January and in August and corresponding assumed T_{EXP}.

HE	January	T_{EXP}	August	T_{EXP}
Residents	223, $i=1$	1	223,$i=1$	1
	154, $i=2$	1	154, $i=2$	1
	411, $i=3$	1	411, $i=3$	1
Tourists	209, $i=1$, 2, 3	1	2299, $i=1$, 2, 3	1
Persons at School	0, $i=1$,2		0, $i=1,2$	
	705, $i=3$	0.25	0, $i=3$	0
Persons at University	0, $i=1$		0, $i=1$,	
	40, $i=2$, 3	0.333	20, $i=2$, 3	0.333
Trade Fair Visitors	10, $i=1$, 2, 3	0.333	9677, $i=1$, 2, 3	0.50
Train Travellers	4798, $i=1$, 2	0.021	4381, $i=1$, 2	0.021
Port Travellers &	1203, $i=1$	0.042	1203, $i=1$	0.042
	0, $i=2$, 3		0, $i=2$, 3	
Workers	501, $i=1$	0.333	501, $i=1$	0.333
	0, $i=2$, 3		0, $i=2$, 3	

Table 3. Daily HE in January and in August in the TRZ_i ($i = 1,2,3$).

	TRZ_1	TRZ_2	TRZ_3
$\mathrm{HE}^{\mathrm{January}}$	334	248	502
$\mathrm{HE}^{\mathrm{August}}$	1055	1736	2513

Table 4. BE in terms of Economic Value (millions of Euros) in the TRZ_i ($i = 1,2,3$).

	TRZ_1	TRZ_2	TRZ_3
BE	6.16	11.14	26.40

each TRZ_i ($i = 1,2,3$) is shown in Table 3. Second, we calculate the resulting portion S^j_{Ai} of the j-th section pertaining to the i-th TRZ. Finally, we compute the value HE^j_i in a such a portion of territory by means of the formula

$$\mathrm{HE}^j_i = A_i \times S^j_{Ai}, \quad i = 1,2,3, j = 1,....,54 \tag{10}$$

Figure 4a and b shows the value of HE^j_i respectively in January and in August in the fraction of the j-th section belonging to the i-th TRZ_i ($i = 1,2,3$).

2.2.2 Building Exposure (BE)

In the BE case, it is assumed that the economic value depends on the surface and location of the buildings. The BE estimation is calculated only in terms of the economic value of the buildings in the TRZ_i ($i = 1,2,3$). The building value is available and freely provided by the Italian National Agency of the Territory (Agenzia Nazionale del Territorio, http://www.agenziaterritorio.it/). This agency gives the economic value of the buildings for each municipality in Italy according to some predefined typology (residential, commercial, industrial), and to their location (streets). We calculate an Averaged Economic Value per m^2 (AEV) for the TRZ of Messina, that results to be equal to 1677.80 Euro per m^2. The BE_i for each TRZ_i ($i = 1,2,3$) is shown in Table 4. Finally, we compute the total BE that equals 43.70 millions of Euros in the TRZ limited by the run-up levels 0.5–10 m.

Typologies and locations of the single buildings are not provided in the ISTAT database, but other very useful data such as the edifice areas are given for each section. They allow us to estimate the BE in terms of economic value using the same procedure of Eq. (10) and introducing the AEV in the formula:

$$\mathrm{BE}^j_i = \mathrm{BA}^j_i \times \mathrm{AEV}, \quad i = 1,2,3, j = 1,....,54 \tag{11}$$

where BA^j_i is the area of the exposed buildings of the j-th section portion in each i-th TRZ. A map of BE^j_i is given in Fig. 4c.

2.3 Vulnerability (V)

The vulnerability represents the fraction of the exposed elements (humans and buildings) that may be destroyed/damaged during a calamitous tsunami event.

Table 5. Number of persons with vulnerable characteristics in the TRZ_i ($i = 1,2,3$).

Vulnerable persons	TRZ_1	TRZ_2	TRZ_3
Age <5	12	3	19
>65	12	32	71
Disabled	15	10	27

Table 6. Number of buildings with vulnerable indicators in the TRZ_i ($i = 1,2,3$).

Vulnerable buildings	TRZ_1	TRZ_2	TRZ_3
Isolated	2	2	9
Not reinforced concrete walls	3	4	14
Bad building conditions	19	17	58

2.3.1 Human Vulnerability (HV)

In various natural hazard assessments, the vulnerability of people and communities can be measured by indicators (Dwyer et al., 2004). The combination of these indicators describes the HV level. In Dwyer et al. (2004), the indicators were related to age, income, residential type, tenure, employment, English language skills, household type, disability, house insurance, health insurance, debt and savings, car, gender. In the present study, two indicators only are chosen on the basis of the peculiarity of the Italian society:

– Age: people over 65 and under 5 are considered more vulnerable.

– Disability: disabled people at home are usually more vulnerable.

The number of people and their ages can be found in the ISTAT database, whereas the number of disabled people living at home is not directly provided by the ISTAT. However, the Ministry of Work and Social Politics in Italy in collaboration with the ISTAT has elaborated an information project indicating the average number of disabled people in each Italian region (http://www.handicapincifre.it/). Disabled people older than 5 yr living at home were 6.6 % of the total population in the Sicily region during the years 2004–2005. We use this general figure also for the population living in the TRZ_i ($i = 1,2,3$) of Messina. We calculate the number of vulnerable persons, VP, as a portion of the residents (that are invariable during the year) because there is no available data on age and disability regarding the tourists, travelers, trade fair visitors, and students. For this reason, VP is constant in January and August. More details are shown in Table 5. Finally, we assume that the greatest part (90 %) of all people younger than 5, older than 65, and disabled are vulnerable and that only a small portion portion (10 %) of residents (not presenting any vulnerable indicator) could be vulnerable (10 %). So that

$$\mathrm{VP} = P_{<5,>65,D} \times 0.90 + (P_{\mathrm{Residents}} - P_{<5,>65,D}) \times 0.10 \quad (12)$$

Also in this case, we used the mean areal density a_i in each i-th TRZ_i ($i = 1,2,3$)

$$a_i = \mathrm{VP}_i / S_{Ai}, i = 1,2,3 \quad (13)$$

and we compute the VP_i^j using the formula

$$\mathrm{VP}_i^j = a_i \times S_{Ai}^j, \quad i = 1,2,3, j = 1,....,54 \quad (14)$$

Finally, the HV_i^j is the fraction of the exposed residents $\mathrm{HE}_{\mathrm{Residents}_i^j}$

$$\mathrm{HV}_i^j = \mathrm{VP}_i^j / \mathrm{HE}_{\mathrm{Residents}_i^j}, \quad i = 1,2,3, j = 1,....,54. \quad (15)$$

in each j-th section and is shown in Fig. 5a.

2.3.2 Building Vulnerability (BV)

According to Papathoma and Dominey-Howes (2003), the BV is related to the material of the building, the row, the number of floors, the building surroundings, the condition of the ground floor, the presence of sea defence in front of the building, and the width of the inter-tidal zone (in general the natural environments) in front of the building. In the present case we use three indicators:

– Isolated Building: they are considered more vulnerable.

– Building materials: not reinforced concrete walls are less resistant to tensile actions and more vulnerable.

– Building conditions: bad conditions of a building increase the vulnerability.

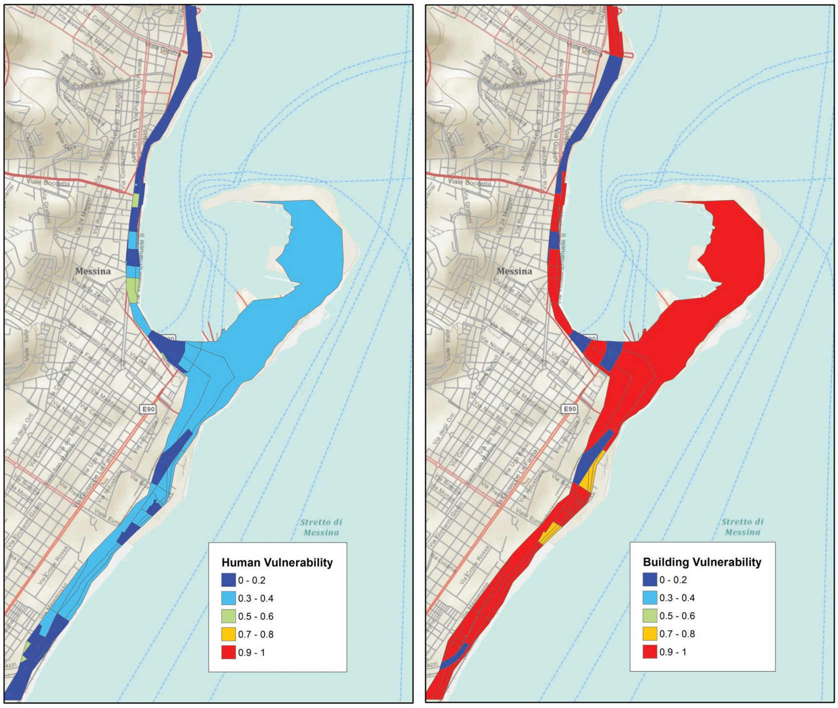
The total area B of the vulnerable buildings covers the buildings presenting at least one of the vulnerable indicators. More details are shown in Table 6.

The BV_i^j is the fraction of BE_i^j calculated considering the AEV in the following equation:

$$\mathrm{BV}_i^j = B_i^j / \mathrm{BE}_i^j \times \mathrm{AEV}, \quad i = 1,2,3, j = 1,....,54 \quad (16)$$

where B_i^j is the total area of the vulnerable buildings of the j-th section portion in each i-th TRZ. The considerable BV value is explained by the high number of buildings in bad conditions in the TRZ as is indicated in Table 6. A map of BV_i^j is given in Fig. 5b.

After the above analysis on the buildings' stock of the Messina area, it is worth making a remark concerning the vertical shelters. The problem of the reduction of the human vulnerability could be related to the building structures



(a) **(b)**

Fig. 5. **(a)** Human Vulnerability HV_i^j and **(b)** Building Vulnerability BV_i^j in each j-th section fraction in the i-th TRZ_i ($j=1,54$ and $i=1,2,3$).

when the importance of the building vertical evacuation is considered (Dall'Osso et al., 2010; Omira et al., 2010; Papatoma et al., 2003a). In the case of a near-source-generated tsunami, the first wave can arrive within minutes and people with limited mobility (seniors, young children or disabled people) are assumed to walk or move slowly, much less than $1\,\mathrm{m\,s^{-1}}$. This vulnerable portion of population could consider vertical evacuation as a fast evacuation option. It is worth it to indicate the number of buildings offering a potential vertical evacuation for each section. We consider the edifices with 5 or more levels as buildings for potential vertical evacuation because more than 4-floored buildings are edifices higher than 10 m. They are indicated by black stars in Figure 1a. More detailed information on the resistant capacity of those buildings to the seismic and tsunami forces are needed in order to indicate those buildings as effective for vertical evacuation. However, this kind of information is not available for the present study.

3 Tsunami damage assessment

In general, the degree of Damage D is defined as $D=\mathrm{EE}\times V$ and quantifies the consequences of a natural event. We computed the Tsunami Damage (TD) in January and August both in the human case

$$\mathrm{HD}_i^j=\mathrm{HE}_i^j\times\mathrm{HV}_i^j,\quad i=1,2,3,\ j=1,\ldots.,54. \tag{17}$$

and in the building case

$$\mathrm{BD}_i^j=\mathrm{BE}_i^j\times\mathrm{BV}_i^j,\quad i=1,2,3,\ j=1,\ldots.,54 \tag{18}$$

in the each portion of the j-th section belonging to the i-th TRZ.

The HD represents the daily number of people potentially affected by a tsunami. The total HD results to be 306 in January and 478 in August in the TRZ limited by the run-up levels 0.5–10 m. Figure 6a and b shows the HD_i^j in January and August. These maps represent respectively the months of the lowest and of the highest human presence in Messina.

These estimations are determined only by using the run-up values in the Bayesian PTHA. We remark, however, that the General Modular Bayesian PTHA procedure (Grezio et al., 2010a) can be used also to deduce other parameters describing the tsunami level of danger like wave energy, water depth, velocity flow or depth/velocity ratio that could be relevant to infer damage. For example, it is known that in the case of loss of human stability in flood water, even low depth can be quite dangerous in presence of high velocity flow (Jonkman and Penning-Rowsell, 2008). In fact, the combination of the momentum instability of the human body (causing toppling) and friction instability (causing sliding) may increase the level of human vulnerability. In particular, people experience difficulties in wading through water also at water depths <0.5 m

(a) (b) (c)

Fig. 6. Human Damage HD_i^j in terms of number of persons **(a)** in January and **(b)** in August, and **(c)** Building Damage BD_i^j in terms of economic value (Euro) in each j-th section fraction in the i-th TRZ_i ($j = 1,54$ and $i = 1,2,3$).

Table 7. HD in January and August and BD (in millions of Euros) in the TRZ_i ($i = 1,2,3$).

	TRZ_1	TRZ_2	TRZ_3
$HD^{January}$	79	77	150
HD^{August}	110	113	255
BD	3.74	5.10	20.12

Table 8. HTR daily in January and August and BTR (in Euro) daily in the TRZ_i ($i = 1,2,3$).

	TRZ_1	TRZ_2	TRZ_3
$HTR^{January}$	1.3×10^{-3}	0.8×10^{-3}	0.0001×10^{-3}
HTR^{August}	1.8×10^{-3}	1.2×10^{-3}	0.0002×10^{-3}
BTR	60.52	54.80	0.015

if its velocity is higher than $3\,\mathrm{m\,s^{-1}}$. On the basis of this consideration, we could expect even higher values of HD in the TRZ_1.

The BD is expressed by the economic value of the building and results to be 28.96 millions of Euros in the TRZ limited by the run-up levels 0.5–10 m. Figure 6c shows the BD_i^j in each j-th portion of each section in each i-th TRZ_i.

Table 7 shows the degree of human and the building damage in the TRZ_i ($i = 1,2,3$).

4 Tsunami Risk assessment

The TR based on the Fournier d'Albe definition of risk (Eq. 1) is equivalent to the TR expressed in terms of degree of damage, that is $TR = \Pi \times TD$.

Considering Eqs. (17) and (18), we calculate

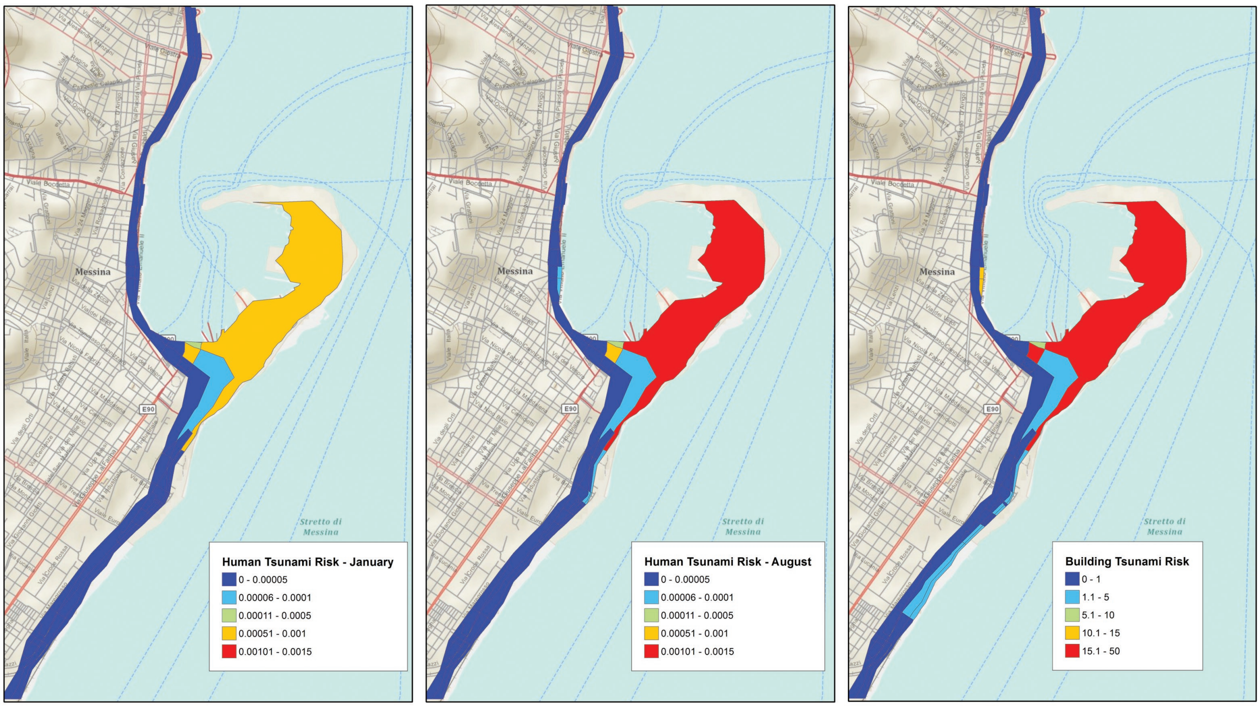
$$HTR_i^j = \pi_i \times HD_i^j, \quad i = 1,2,3, j = 1, \ldots, 54 \tag{19}$$

and

$$BTR_i^j = \pi_i \times BD_i^j, \quad i = 1,2,3, j = 1, \ldots, 54 \tag{20}$$

that are respectively the Human Tsunami Risk (HTR) and the Building Tsunami Risk (BTR) in the j-th fraction area in each i-th TRZ_i ($i = 1,2,3$), where π_i is the occurrence probability of a tsunami impact in each of the three TRZ_i referring to a given time period. In the following calculations we have considered daily occurrence probability. The minimum (in January) HTR_i and the maximum (in August) HTR_i and the BTR_i in each TRZ_i ($i = 1,2,3$) are summarized in Table 8.

The final HTR_i^j maps in January and August in Messina are shown in Fig. 7a and b, and the BTR_i^j map is given in Fig. 7c. From the present study, the number of persons at risk daily in January and August is respectively about 2.1×10^{-3} and 3.0×10^{-3} and the economic value at risk daily is about 115.33 Euro in Messina in the TRZ between 0.5–10 m. This



(a) (b) (c)

Fig. 7. Human Tsunami Risk HTR_i^j in terms of persons **(a)** in January and **(b)** in August, and **(c)** Building Tsunami Risk BTR_i^j in terms of economic value (Euro) in each j-th section fraction in the i-th TRZ_i ($j = 1,54$ and $i = 1,2,3$).

value in an annual time scale is about 42 000 Euro and on a century time scale it is about 4.2 million Euros.

5 Final remarks

The TR assessment taking into account the evaluation of the Hazard, Exposed Elements and Vulnerability (both for the human and building case) is presented here for the first time for the city of Messina. In the present study, the TR is calculated in three tsunami risk zones within the coastal area limited by the run-up levels 0.5–10 m. The Hazard is based on the new General Modular Bayesian PTHA Procedure for the case of submarine seismic sources and submarine mass failures (Grezio et al., 2010a, b). This procedure is innovative for two reasons: (a) the Bayesian procedure is applied to an Italian/European site for the first time using both instrumental and historical data and (b) different types of sources are included to determine the tsunami hazard. The procedure can be further improved by the use of: (a) more advanced tsunami source generation and tsunami wave propagation models, and (b) longer data records. In this respect, we underline that the modular Bayesian PTHA is particularly suitable for the incorporation of any kind of update, in terms of new models and/or data availability. Any improvement will also allow the reliability parameter of Eq. (5) to be increased, making PTHA more precise. At this stage of knowledge, we consider the modules adopted here adequate for a first order approximation of the probability.

We use data from the Italian National Institute of Statistics (on the population, tourists, buildings and many others social aspects), from the Italian National Territory Agency (on the updated economic value of the buildings, their typologies and locations) and from the Train and Port Authorities (on people in transit) plus other data directly collected (on Fair Trade, schools and universities) in order to evaluate the human and building exposure. In the case of Human Exposure, a factor indicating the time of exposition is introduced because people's exposure is not constant but depends on their presence in different places and different periods of the year. We choose January and August, the two most representative months of a generic year, to indicate the minimum and the maximum human presence in Messina. In the case of Building Exposure, the estimated economic value depends on building surfaces and locations. Considering the Italian social characteristics, Human Vulnerability is described by two indicators: age (people over 65 and under 5), and disability (disabled people at home). Building Vulnerability is evaluated in Messina by building indicators that report if the buildings are: isolated, not reinforced by concrete walls and in bad condition. The TR assessment is reported on ArcGIS maps for the tsunami run-up levels of 0.5 m, 3 m, 6.5 m and 10 m using the ISTAT sections of the Messina territory.

These sections delineate the most complete set of available information at the highest resolution for the TR assessment.

The present tsunami risk assessment represents necessarily a lower limit, because it is based on the minimum value of the exposed and vulnerable elements. Many other elements (both material and social) cannot be evaluated at this stage. With the available information, we cannot evaluate reliably many factors that would increase the overall risk. A partial list of these factors contains the vulnerability of tourists, the exposure of many public infrastructure and private propriety, the economic activities damaged by a tsunami, the economic value of facilities such as the Port and the Train Station, the infrastructure (roads, railways and bridges), private property (cars, wagons, ships, goods and products in shops), etc. As a general estimation, we report the mean value of the construction cost of a road in Italy that is 258×10^3 Euro km^{-1} (Maffei and Boccaccini, 2006). Further, we do not consider indirect damages such as the ones due to the disruption of the port that would heavily impact the city economy with significant but not quantifiable economic losses. Moreover, we cannot yet consider the resilience. For example, the Messina Port is crucial for the economic and social connections of the city, and, more important, it is a decisive factor for the capacity of the city to recover after a calamitous event and to retrieve a normal economic, social, and cultural life. All these factors have to be considered in further analyses.

As final remark, we emphasize that the risk calculated here is due only to the tsunami. The combination of a tsunami event with an earthquake event (that could be close in time and could generate a tsunami itself) is not investigated here and the amplification of the catastrophic effects on the vulnerable elements and exposed elements during the tsunami impact phase is also not examined in this study. The appropriate analysis in this case requires a multi-risk assessment (Marzocchi et al., 2012) and was not the primary scope of this PTHA application.

Acknowledgements. The present study was supported by the EU Project TRANSFER. We thank Adriano Cavalieri for helping with ArcGIS and Laura Sandri for the discussions on PTHA. Finally, we thank the two referees for the useful comments that improved the quality of the paper.

Edited by: T. Glade
Reviewed by: G. Papadopoulos and M. González

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