Probabilistic TSUnami Hazard MAPS for the NEAM Region (TSUMAPS-NEAM)
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Guidelines for using TSUMAPS-NEAM S-PTHA

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Tsunami, the Basics.

A tsunami is a natural phenomenon that occurs when a large mass of water, in the sea or a lake, is swiftly shifted generating a series of waves. Tsunamis are known for their potential of flooding the coastal areas and thereby causing, in some cases, loss of life and property damage.

Tsunamis can be triggered by:

- major undersea or near-coast earthquakes that produce a substantial uplift or downshift of the seabed, lake bottom or the coastal area; they are by far the most common cause of tsunamis and TSUMAPS-NEAM deals with hazard from earthquake-generated tsunamis only;
- large submarine or subaerial landslides, or rock falls, often as a result of an earthquake or volcanic activity;
- volcanic eruptions, submarine explosions, caldera collapses, or pyroclastic flows;
- sudden changes in atmospheric pressure;
- meteorite impacts.

Tsunami waves and ordinary wind waves are very different from one another. Wind waves are generated when the wind disturbs the water surface and usually have periods (time interval required for one full cycle of a wave) on the order of a few tens of seconds. Conversely, tsunami waves are wave trains characterized by a sequence of peaks and troughs departing in any direction from the source. Tsunamis involve the movement of the whole water column (from the sea bottom to the surface of the water body) and have periods of several minutes up to 1 hour or more. Consequently, the amount of energy that characterizes tsunami waves is much higher than that of wind waves.

Tsunami generation from earthquakes is largely controlled by the spatial extent, distribution, and temporal features (time history) of the co-seismic deformation of the sea bottom, which in turn depend on the earthquake characteristics (rupture size and geometry, faulting mechanism, spatial and temporal slip distribution). Generally speaking, earthquakes characterized by vertical motion on relatively steep faults are the most tsunamigenic, and tsunami energy is mostly directed outward from the source zone perpendicularly to the broad side of the fault.

In the open sea, tsunamis behave much like long-period (shallow water) linear waves. Hence, they dissipate little energy, travel long distances, and are attenuated almost only by geometrical spreading. They propagate fast in deep waters at a speed which is the square root of the water depth times the gravitational acceleration. Consequently, tsunami energy focusing-defocusing is controlled by bathymetric features, for example by refraction and interferences between different waves. Tsunamis can also show frequency dispersion, especially affecting relatively small wavelength components introduced by complexities of the source features. When approaching the coast during the shoaling, the tsunami wave then slows down and, due to the conservation of energy, its amplitude increases, and its wavelength reduces progressively. The higher the ratio between tsunami height and water depth, the higher the non-linearity of the shoaling. The steepness of the coastal slope conversely enhances linearity. Strong wavefront steepening may also occur, and it may lead to wave breaking.

When a tsunami wave hits the coast, the inundation evolution becomes a complex non-linear phenomenon controlled by the interaction of the incident wave features with the topography. The run-up (the topographic height that the wave reaches inland) could exceed twice the amplitude of the wave at the coastline because of the momentum of the wave that can push inland the entire column of water even for considerable distances along the slopes. The maximum inundation distance and the maximum run-up can be highly variable depending on local conditions.

Generally, the highest run-up values are observed in coastal areas where a steep slope is present or where topographic features lead to wave focusing phenomena. Long inland flooding distances may affect coastal areas with a gentle slope and scarce vegetation that are characterized by limited roughness and absence of obstacles, where the energy of tsunami waves dissipates slowly.

Further and more thorough treatment of the above topics can be found in Lynett (2008), Geist and Oglesby (2014), and references therein.

TSUMAPS-NEAM Hazard Model

The probabilistic quantification of the tsunami hazard (PTHA - Probabilistic Tsunami Hazard Assessment) is catching on as a standard methodology to estimate tsunami hazard (Geist & Lynett, 2014; Grezio et al., 2017).

From now on, we indicate the PTHA for earthquake-generated tsunamis as Seismic-PTHA (S-PTHA).

TSUMAPS-NEAM yielded the first S-PTHA model which is homogeneous at a scale as large as that of the entire NEAM region, i.e., a region that embraces north-eastern Atlantic (from the coast of Africa to Norway, Greenland, and Iceland), the Mediterranean and the connected seas (Aegean, Marmara, and Black Seas).

TSUMAPS-NEAM S-PTHA builds upon robust datasets and methods developed in previous projects at local, regional, and global scales. It also relies on innovative and robust procedures implemented during the development of the project.

As every hazard assessment, the implementation of TSUMAPS-NEAM S-PTHA required several potentially subjective decisions to be made, such as the selection of scientifically-acceptable alternative models (to represent hazard uncertainty) and the weighting of the adopted choices (to represent their scientific credibility). Renowned scientists from all around the world helped the TSUMAPS-NEAM Team throughout the development of this complex procedure with their expertise and voluntary dedication. Therefore, this model is the result of a high and complex interaction within a broad international scientific community.

More specifically, a transparent and documented multiple-expert process was implemented for managing and reducing the subjectivity of these potentially critical choices. This process included formal elicitations of a Pool of Experts, and a participatory review of methodology and results by a further group of experts, called Internal Reviewers (FIGURE 1).

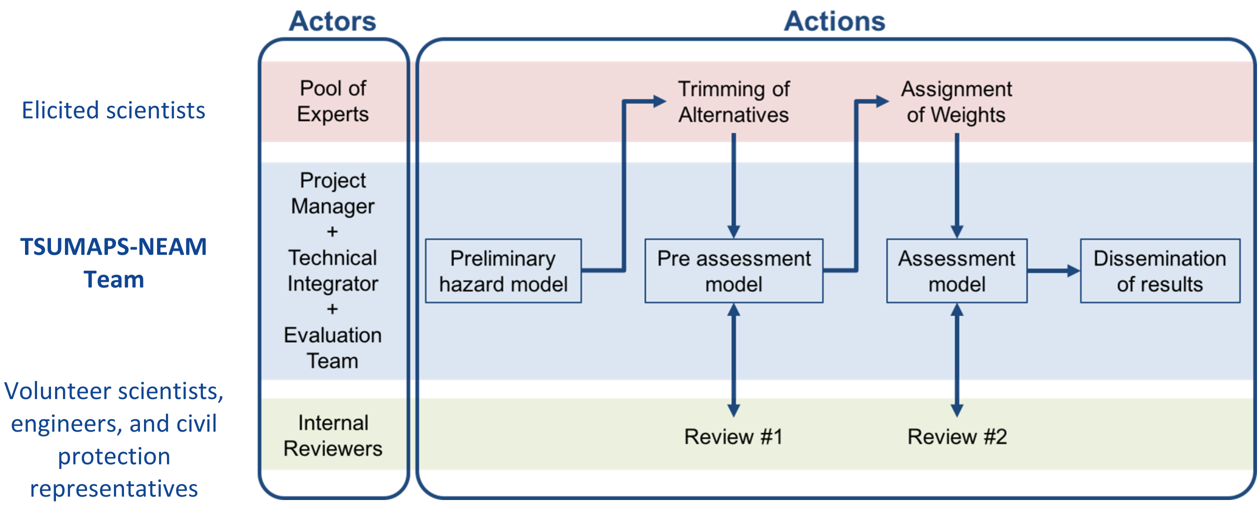

FIGURE 1: Simplified flowchart of the different roles and actions of the different groups of experts involved in TSUMAPS-NEAM.

The model uncertainties have been finally estimated with the ensemble modeling technique (Selva et al., 2016), also recently adopted for seismic and volcanic probabilistic hazard assessments (Marzocchi and Jordan, 2014; Marzocchi et al. 2015; Selva et al. 2018).

The results of the TSUMAPS-NEAM project (FIGURE 2) are available to the public on the internet (http://www.tsumaps-neam.eu/), in the form of hazard curves, hazard and probability maps, calculated in specific Points of Interest (POIs), for a specific tsunami intensity measure, referred to as the Maximum Inundation Height (MIH). These concepts will be briefly introduced in the next sections.

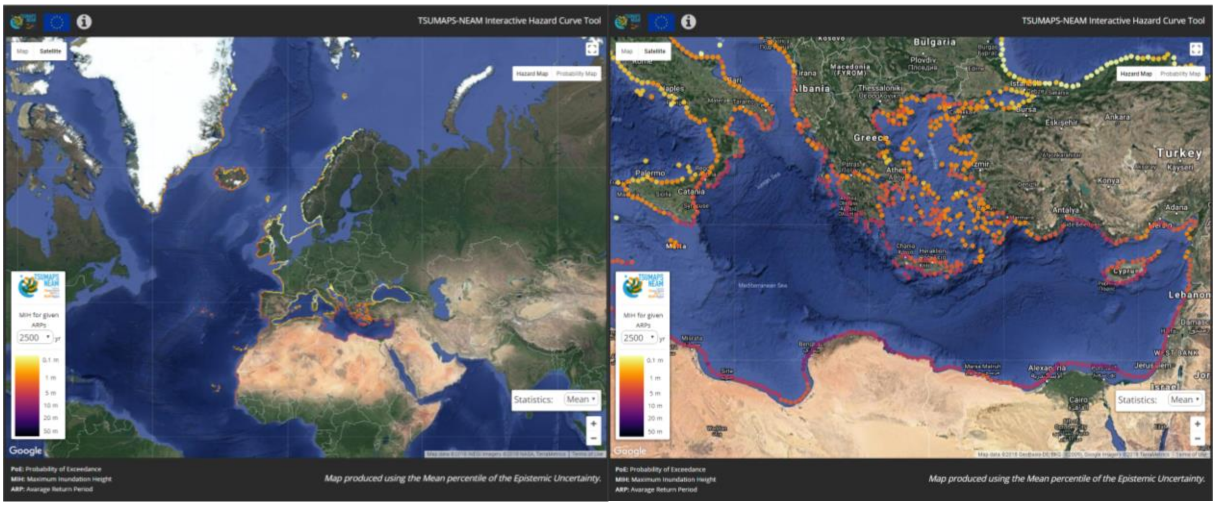

FIGURE 2: The TSUMAPS-NEAM model hazard map for the mean epistemic uncertainty and a return period of 2500 years (left), and a close-up view of the eastern Mediterranean area (right).

The Hazard Intensity Metrics and the POIs

The hazard values are calculated at specific Points of Interest (POIs). The POIs are selected along the -50 m bathymetric line. Each POI represents a nearby coastal area, called target area (FIGURE 3). In TSUMAPS-NEAM we considered more than two thousand POIs distributed along the NEAM coastlines. These points are spaced, on average, at about 20 km from one another. There are 1,076 points in the North-East Atlantic Ocean; 1,130 points in the Mediterranean Sea; and 137 points in the Black Sea.

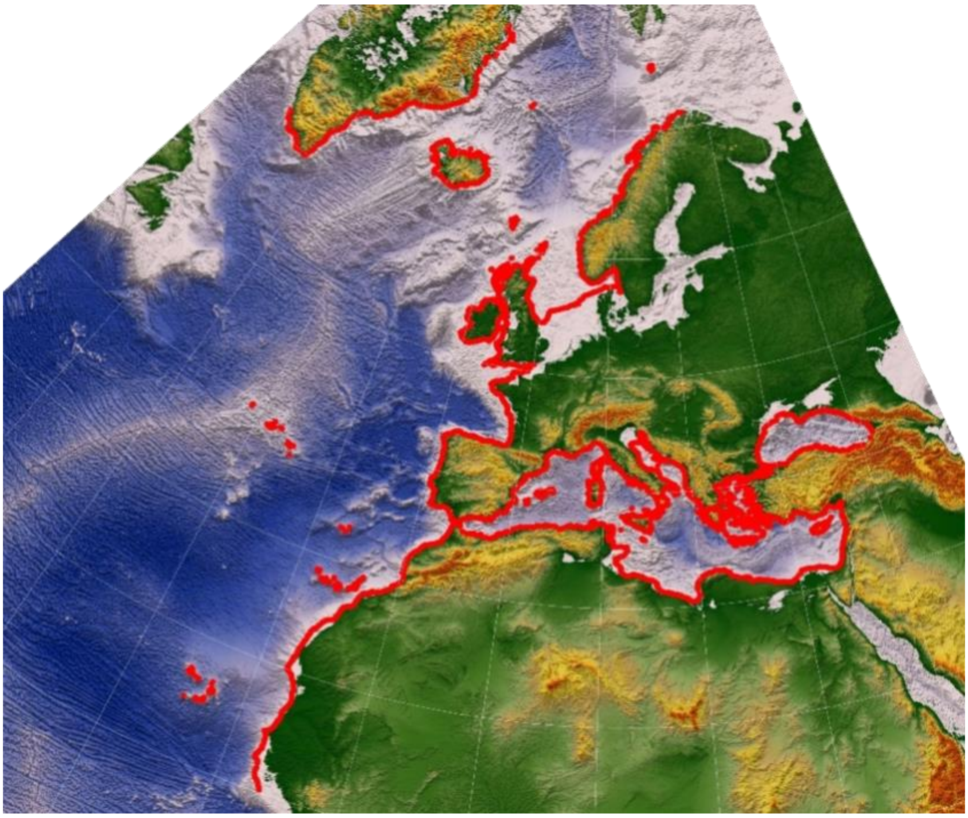

FIGURE 3: The POIs considered in TSUMAPS-NEAM (red dots) along the coasts of the NEAM (North-Eastern Atlantic, the Mediterranean, and the connected Seas) Region. See http://www.ioc-tsunami.org/ for further details.

Like studies at global, regional, and local scales (e.g. Davies et al., 2017), the intensity parameter used in the hazard model is the maximum inundation height (MIH, FIGURE 4), which is the maximum height reached by the wave and measured from the mean sea level along topographic profiles orthogonal to the coastline (water height plus topographic height). However, the MIH calculated at all the POIs represents the tsunami intensity in the target area associated to each POI, not just along a single profile.

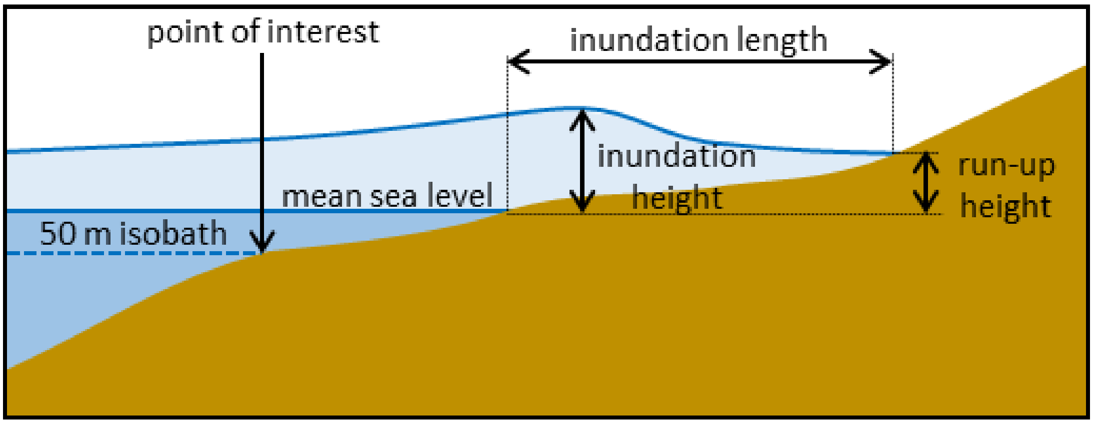

FIGURE 4: Sketch of the different quantities discussed in the text.

The MIH reported by TSUMAPS-NEAM necessarily represents an average value over this area, as it may vary laterally along the coast behind the POI. Local MIH (and maximum run-up) values along the coast can be 3-4 times larger than the MIH estimated by the hazard model.

The MIH of each seismic scenario is here based on the following:

1) numerical models of the tsunami wave related to all the considered earthquake scenarios;
2) a parametric amplification along the single 1D profile depending on the local bathymetry, on the period and the polarity of the incident offshore wave from each scenario (calculated at the 50 m isobath);
3) a conditional probability that models the lateral (coast-parallel) variability, due to each scenario, of MIH in the target area represented by each POI.

The resulting distributions quantify the probability for different values of the MIH at a random point within the target area corresponding to a POI for each scenario. The combination of this information with the probability of occurrence of each scenario produces in each POI the hazard curves, which are described in the next section.

Hazard Curves, Hazard and Probability Maps

A hazard curve is a plot of the results of mathematical calculations that integrate the probability of each considered seismic source with the tsunami intensity it may generate (FIGURE 5, Left). The hazard curve thus expresses the probability of exceedance versus an “intensity measure level” in a given period, called the “exposure time.” In other words, each point on the curve tells how frequently an event of a particular intensity is surpassed in the future in the target area. The adopted exposure time in TSUMAPS-NEAM is 50 years, and the hazard curves are calculated in each of the POIs adopting as intensity measure the MIH, as described in the previous section

Probability and frequency of an event in time are linked together so that at each probability value corresponds to a so-called average return period (ARP) which is the average time span between two consecutive events of the same intensity. The probability of exceedance is always a number between 0 and 1, often expressed as a percentage (e.g., a probability equal to 0.3 is often reported as 30%).

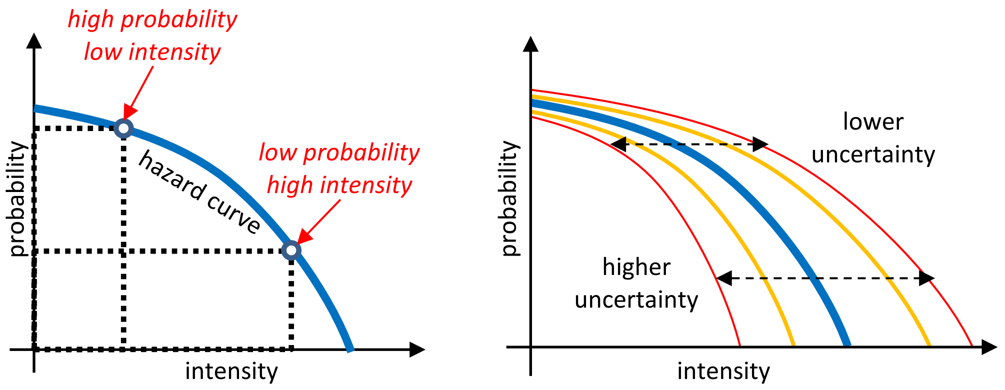

FIGURE 5: Left, a sketch of a hazard curve; Right, a sketch of a suite of percentiles expressing the uncertainty of the hazard model.

All models have a certain degree of uncertainty, including hazard models. Several hazard curves can be shown in a single plot to represent this uncertainty, through a quantity called percentile (FIGURE 5, Right). This uncertainty represents the variability of the hazard curve when different scientifically acceptable modeling choices are implemented. For example, the hazard curve at the 50-percentile indicates that 50% of the scientifically acceptable models provide hazard curves with probability values smaller than its values. Looking at how the percentiles are spread apart, we can evaluate the level of uncertainty of the hazard model.

As discussed in the previous section, the MIH values reported in the x-axis of the hazard curves necessarily represents an average over the area that each POI represents. Within this area, MIH may vary laterally, and local MIH (and maximum run-up) values along this coast can be 3-4 times larger than the MIH reported by the TSUMAPS-NEAM hazard curves.

To traslate the hazard into a map, i.e., to gain a geographic appreciation of the hazard, the starting points are the hazard curves at all POIs. In this perspective, there are two options: hazard maps and probability maps.

For making a hazard map, the MIH corresponding to a chosen design probability (y-axis of hazard curves) is extracted at each POI (FIGURE 6, Top). The POI colors on the hazard map scale according to the MIH measured in meters. Engineers and other hazard specialists generally use this type of maps.

For making a probability map, the probability of exceedance in 50 years corresponding to a chosen value of the MIH (x-axis of hazard curves) is extracted at each POI (FIGURE 6, Bottom). The POI colors on the probability map scale according to the probability expressed by a number between 0 and 1. This type of maps is more useful to communicate the hazard to administrators, decision makers, and the general public.

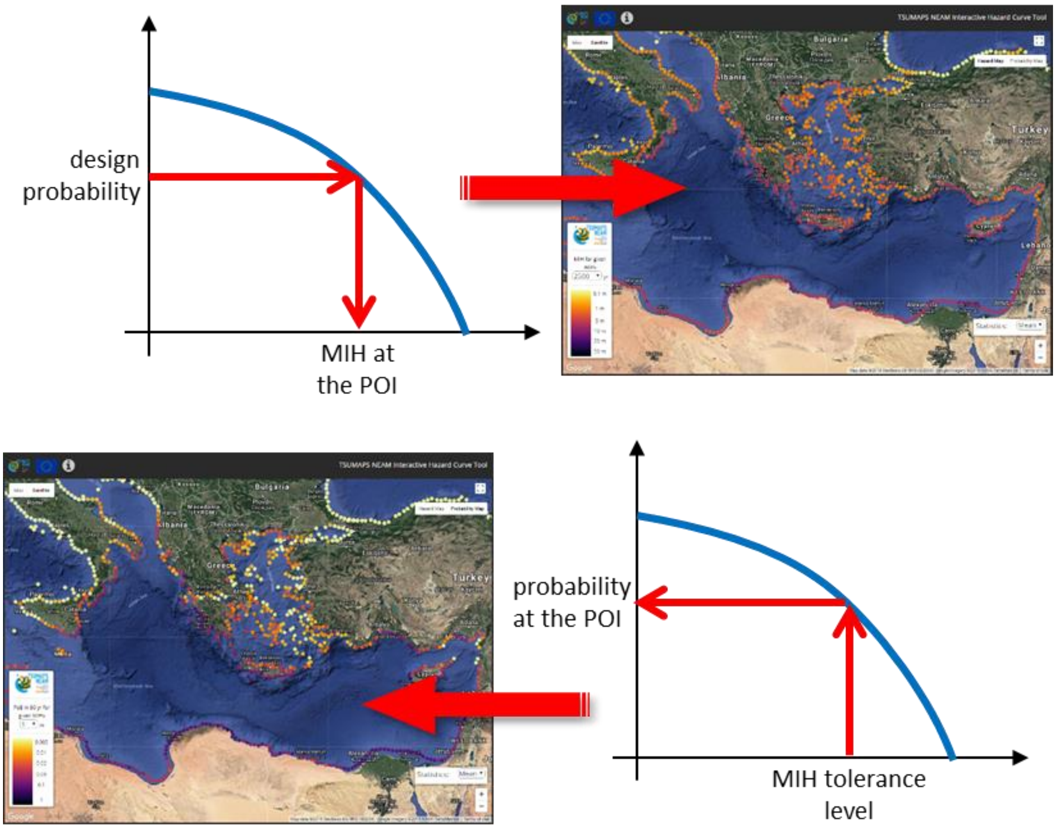

FIGURE 6: Top, a hazard map, i.e. the values of MIH in meters at each POI, obtained by cutting the hazard curves at a given probability of exceedance in 50 years; Bottom, a probability map, i.e. the probability of exceedance in 50 years, obtained by cutting the hazard curves at a given MIH value.

Limitations

The TSUMAPS-NEAM hazard model shares the same limitations as any other hazard model.

A probabilistic hazard model attempts to predict future hazard at a location. However, a model cannot ever be an exact representation of the reality or predict the future hazard precisely.

One of the results of the hazard model is, for example, the ARP of a given MIH being exceeded at some location. The longer the ARP, the scarcer the observations for testing and eventually falsifying the model. This circumstance asks for caution when using hazard results for practical applications, particularly for long ARPs.

Tsunamis are rather low-frequency (but possibly high-impact) events. Therefore, tsunami hazard models, in comparison with hazard models for more frequent phenomena, have typically even scarcer observations to be based on and for calibration. This circumstance introduces large uncertainty in the hazard model.

These data, such as long records of a measured run-up at a specific coastal site, are even scarcer in the NEAM region than in other regions characterized by more frequent (large) earthquakes, as it may be the case for Chile, for example.

For this reason, following a common and almost standard practice (Geist and Lynett, 2014; Grezio et al., 2017), the TSUMAPS-NEAM hazard model was built by modelling earthquake probability and tsunami generation and impact from these earthquakes, rather than building the hazard model directly from available tsunami data, which is an almost impossible task.

The TSUMAPS-NEAM model is the result of a project which, likewise any other project, relies on finite material and human resources. We strived for an optimal trade-off between feasibility and depth of the analysis. However, some further analyses, a collection of new data, and general improvements may be achieved in a future updated version. For example, the impact on hazard results of the uncertainty of the bathymetric model used for tsunami propagation was not assessed, because this task was out of reach for the project. Only a qualitative check of the differences in the results of some scenarios performed with a different bathymetric model was performed. This circumstance and other issues are reported in the documentation, including some other points raised by the reviewers which could not be addressed for practical reasons.

Being a regional model, its resolution and spatial completeness are limited. Its primary purpose, and consequently usage, is that of a screening tool for prioritizing further higher-resolution hazard and risk assessments at a more local scale.

The next section will describe a couple of potential use-cases. They are just examples, however. Any further application reusing hazard data for risk-management applications and decision making is not necessarily straightforward. We recommend to always rely on the work done by hazard and risk specialists.

Another general recommendation concerns the use-case related to evacuation planning. This model was developed as a tool for elaborating emergency plans at the local scale (or national scale), but for the time being it offers a starting point for future and more detailed studies.

If the local scale is considered in any application, great caution is needed, and it must be understood that very large uncertainty characterizes this application. These uncertainties are necessarily larger than those of a local high-resolution model, which should not and cannot be replaced or superseded by a low-resolution regional-scale analysis.

Potential Use-Cases

Establishing a regional long-term probabilistic tsunami hazard assessment for seismic sources is the first step to be undertaken for starting local and more detailed hazard and risk assessments and then risk management. Coastal regulation and planning, building code definition, and safety of critical infrastructures all depend on these actions. The main advantage of the probabilistic approach in comparison with classical scenario-based methods is that it allows engineers to perform spatially-homogeneous quantitative risk-analysis, and decision-makers to base their choices on quantitative cost-benefit analysis and comparative studies between different areas.

From Long-Term Hazard to Evacuation Maps for Tsunami Early Warning

People can become aware of an impending tsunami by warnings issued by a National Authority or by observing natural signs, such as strong and unusually long shaking, receding sea, roars from offshore. It is crucial that people knows in advance the possible escape routes toward higher ground.

In the absence of a probabilistic tsunami hazard map, the local authorities usually follow the experts' advice coming from the scientific community. This behavior sometimes leads to the decision of setting the limit of the tsunami hazard zone at a distance from the coast that corresponds to a certain topographic height or to a maximum tsunami run-up. These distances may be spatially very inhomogeneous because they hardly contemplate all the possible scenarios. Using probabilistic tsunami hazard maps can help to make this decision less subjectively. The inundation corresponding to a design probability or ARP, considering uncertainty for increasing safety, can be chosen. This type of approach is being followed in New Zealand. The Italian Civil Protection is also following this approach for establishing the national guidelines for the local planning against tsunamis.

Setting priorities for Local Probabilistic Inundation Maps in Hazard and Risk Analyses

Local hazard analyses can be expensive and time-consuming and should then be standardized and prioritized. Standardization can be based on the comparison with a common regional analysis. A prioritization based on the selection of an ARP suitable for a specific application (e.g., an ARP of 2,500 years is being proposed for building codes by civil engineers in the USA) can help the work of decision makers. The priority assessment can be done by comparing the regional-scale hazard at different locations for that specific ARP. Other aspects to take into consideration are the locally exposed coastal population or the infrastructures.

Local tsunami hazard analysis (FIGURE 7) is computationally expensive, requiring the use of high-performance computers, provided that high-resolution digital elevation models be available for nearshore and onshore areas. To limit the computational cost, the analysts need to select a limited number of high-resolution inundation scenarios. The relevant scenarios for the site under examination can be selected using the regional TSUMAPS-NEAM results, and then perform detailed simulations without compromising the results of the analysis.

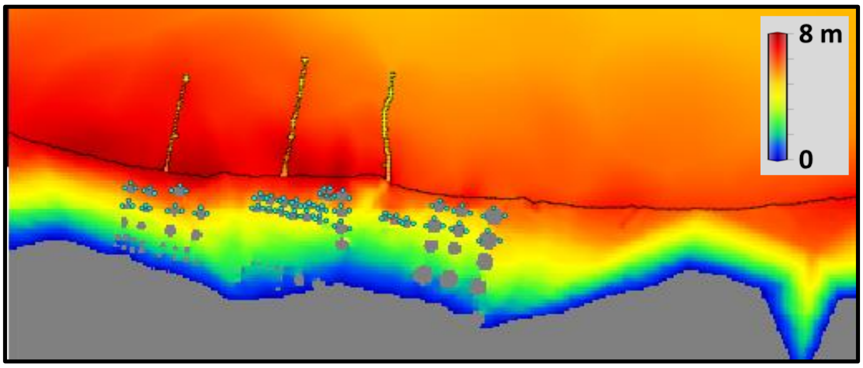

FIGURE 7: Example of a high-resolution tsunami inundation map showing the maximum wave height in the Milazzo Port, southern Italy, for a nearby magnitude 8 earthquake.

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