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Tsunami hazard, warning, and risk reduction in Italy and the Mediterranean Sea: state of the art, gaps, and future solutions

Stefano LORITO[1,*], Alessandro AMATO[1], Lorenzo CUGLIARI[1], Fabrizio ROMANO[1], Roberto TONINI[1], Cecilia VALBONESI[1,2], Manuela VOLPE[1]
[1]National Institute of Geophysics and Volcanology (INGV), Rome, Italy
[2]Department of Legal Sciences, University of Florence, Florence, Italy

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Abstract: Historical catalogues show evidence for about 300 tsunamis in European coastal waters since 1600 BC, and tsunami hazard models like the NEAMTHM18 provide the probability of future inundation from earthquake-induced tsunamis. A recent wake-up call came from the 2020 M_W7.0 Samos-İzmir earthquake and the following moderate, damaging tsunami. Five accredited Tsunami Service Providers (TSPs) run by IPMA (Portugal), CENALT (France), INGV (Italy), NOA (Greece), and KOERI (Turkey), and several national centers monitor the seismicity and provide tsunami alerts in the framework of the UNESCO Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (NEAMTWS). In this paper, we focus on the state of the art of earthquake-induced tsunami risk reduction and coastal planning in Italy from the perspective of the Centro Allerta Tsunami (CAT), the INGV NTWC (National Tsunami Warning Center) and TSP. We will emphasize some limitations to draw future directions for better preparation and towards the full implementation of the tsunami warning "last-mile".

Key words: Tsunami, earthquakes, Mediterranean Sea, hazard, early warning, coastal planning, Italy

1. Introduction

The 2004 Indian Ocean tsunami, which caused widespread consequences, and the 2011 Japan tsunami, which caused the subsequent nuclear disaster, were initiated by large magnitude subduction earthquakes (the M_W9.2 Sumatra-Andaman and M_W9.0 Tohoku-Oki events, respectively), the most common cause for the largest tsunamis worldwide (e.g., Shearer and Burgmann, 2010; Lorito et al., 2016; Uchida and Burgmann, 2021). We cannot exclude that comparably large events will also occur in the Mediterranean Sea (e.g., Kagan and Jackson, 2013; Valle et al., 2014), which is characterized by high vulnerability and exposure of coastal settlements (e.g., Wolff et al., 2020). Historical catalogues document about 300 tsunamis in European coastal waters since 1600 BC, with evidence for tsunami impact retrieved from historical sources, and, despite the always lively debate about their origin (e.g., Cox et al., 2020), from geological evidences (Maramai et al., 2014; 2021; Papadopolous et al., 2017). On the other hand, tsunami hazard in the region is assessed by the recent regional model NEAMTHM18, which provides the probability of future earthquake-induced tsunami inundation in the NEAM region (Basili et al., 2021). A recent wake-up call to consider tsunamis as a serious threat in the region came from the 2020 M_W7.0 Samos-İzmir earthquake and the following moderate, damaging tsunami, reaching up to 3 m above the sea level on both the nearby Greek and Turkish coasts (Dogan et al., 2019; Triantafyllou et al., 2021).

In the last two decades, some countries in our region are making great efforts to protect their coastlines from tsunamis. Five accredited Tsunami Service Providers (TSPs) provide tsunami alerts in the transnational framework of the NEAMTWS; additionally, a few national centers operate at the national level. The TSPs operate under the coordination of the Member States of the Intergovernmental Oceanographic Commission of UNESCO (UNESCO-IOC), exerted through an Intergovernmental Coordination Group (ICG, e.g., UNESCO-IOC, 2017a). For earthquake and tsunami detection, the TSPs exploit seismic and coastal sea level monitoring networks, such as the sea level data monitoring facility hosted by VLIZ on behalf of UNESCO-IOC, which provide real-time sea level observations from many providers (http://www.ioc-sealevelmonitoring.org).

Additionally, some UNESCO-IOC Member States have started implementing both long-term coastal planning and emergency response plans. These involve the

* Correspondence: stefano.lorito@ingv.it

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realization of dedicated infrastructures or the exploitation of the existing ones for the local distribution of tsunami warning messages and the preparation of evacuation maps (for Italy, see Tonini et al., 2021).

This paper reviews the end-to-end approach to tsunami risk reduction and coastal planning in Italy. Without attempting to be exhaustive, we touch upon elements that we consider necessary based on our experience in national and international contexts as scientists as well as TSP. The descriptions of the diverse and complementary elements are accompanied by a critical analysis of the existing gaps. Addressing these gaps may guide future improvements of the tsunami early warning system and disaster mitigation in Italy, and may perhaps serve as a term of comparison to other countries. In Table, a list of the acronyms used throughout the text is provided.

2. CAT-INGV in the NEAMTWS

The tragic Indian Ocean tsunami on 26 December 2004, in which over 250,000 lives were lost around the Indian Ocean region, was a game-changer because it triggered the first truly globally coordinated tsunami risk management initiative. UNESCO-IOC received a mandate from the international community to coordinate the establishment of regional tsunami warning systems, besides the one already operating in the Pacific Ocean (http://t.ly/Gbak; http://www.ioc-tsunami.org). The world's oceans were "divided" into four macro-regions, namely the Caribbean and adjacent regions, Indian Ocean, Pacific, and NEAM; each has its tsunami warning and mitigation system coordinated by intergovernmental bodies. In our macro-region, the formation of the ICG/NEAMTWS led to the establishment, culminated with the formal accreditation, of 5 TSPs serving the entire NEAM region, namely IPMA (Portugal), CENALT (France), INGV (Italy), NOA (Greece), and KOERI (Turkey) (UNESCO-IOC, 2015; UNESCO-IOC, 2017a; UNESCO-IOC, 2020; http://neamtic.ioc-unesco.org/; Figure 1).

The formal accreditation regarded mostly scientific, technical, procedural, and infrastructural aspects of the "upstream" component of the system, that is in charge of the earthquake and tsunami monitoring and detection, and the issuance of the first alert. Nonetheless, each TSP operates within a broader framework, to create the initial and boundary conditions for the initiation of the TSP operations. The institutions in each of the UNESCO-IOC Member States that have set up a TSP have committed themselves to provide and maintain their infrastructures, produced an organizational effort, and developed cutting-edge scientific research and technological advances, in collaboration with and, in some cases, following the example of their colleagues worldwide. Governments and other authorities, especially the Civil Protection agencies, in close cooperation with tsunami experts, developed alert dissemination tools, set up a dedicated legal framework, designed emergency planning, and started to prepare the population with education campaigns.

Like for the other NEAMTWS TSPs, the tsunami warning operations of CAT-INGV (Centro Allerta Tsunami at Istituto Nazionale di Geofisica e Vulcanologia; Tsunami Alert Center at National Institute of Geophysics and Volcanology; https://www.ingv.it/cat/en/) are based on seismic detection and characterization; elaboration of tsunami forecasts and alert levels; potential tsunami detection at coastal tide-gauges for confirmation/cancellation of an alert (for details see Amato et al., 2021). The monitoring area of the CAT-INGV is the entire Mediterranean Sea. The seismic characterization at CAT-INGV is based on national and Euro-Mediterranean seismic networks and the Early-Est software (Lomax and Michelini, 2009; Bernardi et al., 2015 and references therein). A Decision Matrix (hereinafter DM) uses rapid seismic location and magnitude estimates to retrieve alert levels that increase with the earthquake magnitude and decrease with the distance from the epicentre, focal depth, and the landward distance from the coastline. It is quite a "super-fast" and worst-case oriented tool.

2.1. Gaps in TSP operations, and remedies

Some further developments are needed both in the forecasting approach and in the instrumental coverage or data integration.

The applicability of the DM has been questioned since its inception in the NEAMTWS (e.g., Tinti et al., 2012). Using only earthquake location and magnitude, the DM does not take into account some complexities such as the tsunami source directivity or the different tsunamigenic potential of dip-slip as compared to strike-slip faults. There is indeed an extreme tsunami source variability in the Mediterranean that would need to be taken into account (Selva et al., 2021a). Moreover, the DM does not consider the complexity of the tsunami energy distribution during propagation over a realistic bathymetry. CAT-INGV is working to replace the DM with the Probabilistic Tsunami Forecasting (PTF, Selva et al., 2021b), which exploits tsunami numerical simulations (e.g., Molinari et al., 2016), introduces more source complexity (e.g., Scala et al., 2020), and explicitly deals with uncertainty quantification.

Regarding the observation systems, it is sufficient to have a cursory look at the ORFEUS seismic (https://www.orfeus-eu.org) and the VLIZ sea level (http://www.ioc-sealevelmonitoring.org) data facilities to realize that there is a gap in instrumental coverage to the South, which may limit the rapidity and the accuracy of the seismic and tsunami estimates for coastal and offshore sources bordering northern African countries. A diplomatic and networking effort is ongoing to try to address this issue,

Table. List of acronyms.

AGITHAR	Accelerating Global science In Tsunami HAzard and Risk analysis
ANPAS	Associazione Nazionale Pubbliche Assistenze
ASTARTE	Assessment, STrategy And Risk Reduction for Tsunamis in Europe
CAT-INGV	Centro Allerta Tsunami INGV
CENALT	CENtre d'Alerte aux Tsunamis
ChEESE	Center of Excellence in Solid Earth
CIMA	Centro Internazionale in Monitoraggio Ambientale
CINECA	Consorzio INteruniversitario pEr il Calcolo Automatico dell'Italia Nord Orientale
COST	European Cooperation in Science and Technology
DM	Decision Matrix
EMODNET	European Marine Observation and Data Network
EMSO-ERIC	European Multidisciplinary Seafloor and water-column Observatory - European Research Infrastructure Consortium
ENI	Ente Nazionale Idrocarburi
EPOS-ERIC	European Plate Observing System - European Research Infrastructure Consortium
EU	European Union
EWRICA	Early-Warning and Rapid Impact Assessment with real-time GNSS in the Mediterranean
DPC	Dipartimento di Protezione Civile
GFZ	German Research Centre for Geosciences
GNSS	Global Navigation Satellite System
GPU	Graphics Processing Unit
GTM	Global Tsunami Model
HPC	High Performance Computing
ICG	Intergovernmental Coordination Group
INGV	Istituto Nazionale di Geofisica e Vulcanologia
IPMA	Instituto Português do Mar e da Atmosfera
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale
JRC	Joint Research Center
KOERI	Kandilli Observatory and Earthquake Research Institute
NEAM	North-eastern Atlantic, the Mediterranean and connected seas
NEAMTHM18	NEAM Tsunami Hazard Model 2018
NEAMTIC	NEAM Tsunami Information Center
NEAMTWS	Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas
NGI	Norwegian Geotechnical Institute
NOA	National Observatory of Athens
NOANET GNSS	NOA GNSS Network
NTWC	National Tsunami Warning Center
ORFEUS	Observatories & Research Facilities for European Seismology
PRACE	Partnership for Advanced Computing in Europe
PTHA	Probabilistic Tsunami Hazard Analysis
PTF	Probabilistic Tsunami Forecasting
ReLUIS	Rete dei Laboratori Universitari di Ingegneria Sismica
RING	Rete Integrata Nazionale GPS
SiAM	Sistema di Allertamento nazionale per i Maremoti

Table. (Continued).

SMART Cables	State Messaging and Archive Retrieval Toolset Cables
SOP	Standard Operational Procedures
TCS	Thematic Core Service
THM	Tsunami Hazard Model
TNC	Tsunami National Contact
TSP	Tsunami Service Provider
TSUMAPS-NEAM	Probabilistic TSUnami Hazard MAPS for the NEAM Region
TWFP	Tsunami Warning Focal Point
TWS	Tsunami Warning System
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNESCO-IOC	Intergovernmental Oceanographic Commission of UNESCO
VLIZ	Vlaams Instituut voor de Zee (Flanders Marine Institute)

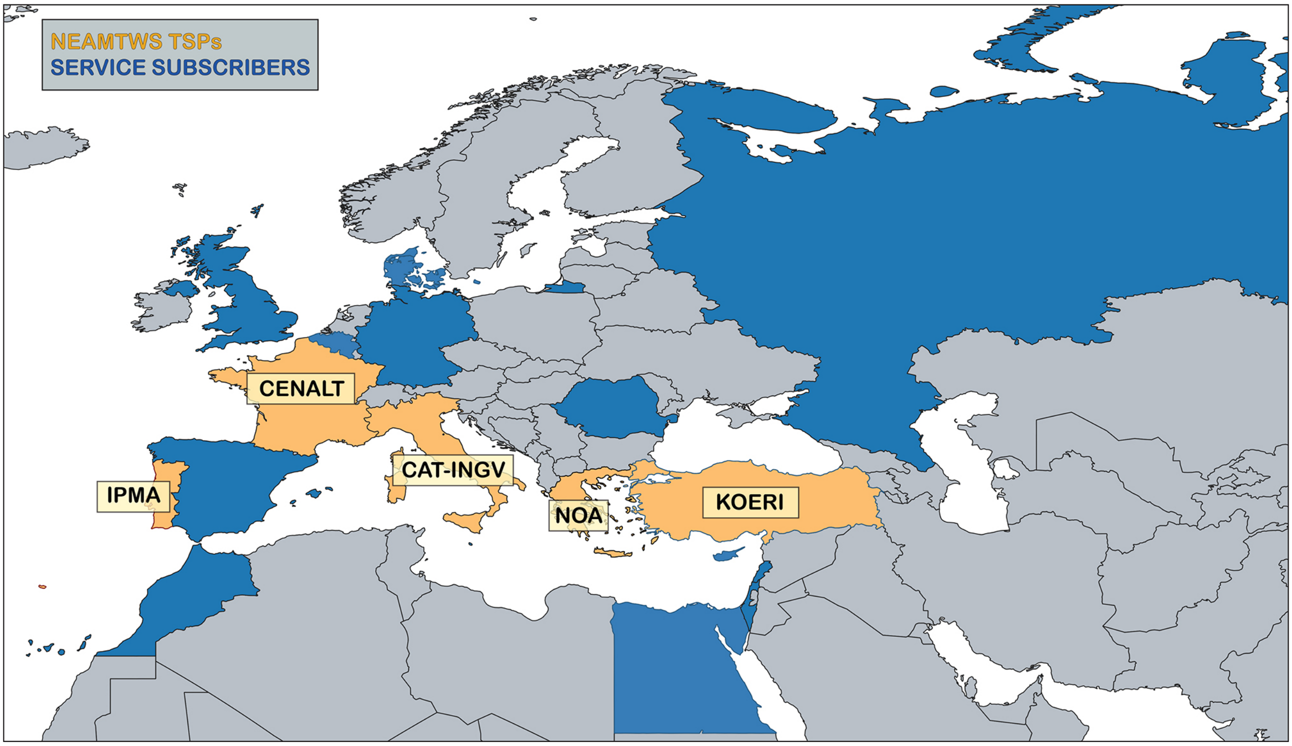

Figure 1. The TSPs (in orange) operating within the NEAMTWS and the UNESCO-IOC Member States (in blue) that are subscribed to their services. Some Member States have constituted their own NTWCs, appointed TWFPs, and TNCs.

for example by means of high-level actions conducted by the ICG/NEAMTWS Secretariat, sometimes jointly with other initiatives, such as those funded by EU DG-ECHO (http://t.ly/ki47).

Modern approaches to near-field earthquake and tsunami detection and characterization involve usage of real-time GNSS data, which may for example contribute to nonsaturating magnitude estimates for large earthquakes (e.g., Ruhl et al., 2017). The first real-time GNSS streams will be soon integrated by CAT-INGV and NOA, using data from their own GNSS networks (RING network, http://ring.gm.ingv.it; NOANET network, http://geodesy.gein.noa.gr:8000/nginfo/). GFZ (German Research Centre for Geosciences) is contributing to the implementation of real-time data streams and to the development of techniques for real-time source characterization in the framework of the EWRICA project in which several TSPs play the role of end-users and advisors.

Additionally, it is worth mentioning that there are no offshore "tsunameters" in the whole Mediterranean Sea. This limits the capability of TSPs to confirm or cancel alerts after an earthquake and before the first waves have reached the coasts. As a first remedy to increase detection power of the sea level network, in 2021, ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale; Italian Institute for Environmental Protection and Research) has installed six additional tide-gauges, which are being acquired by CAT-INGV. They are equipped with pressure-meters on several remote islands and as much as possible outside of harbors (http://t.ly/o62H). ISPRA is also testing relatively low-cost offshore GNSS buoys in collaboration with the EU Joint Research Centre (JRC, https://ec.europa.eu/jrc/en). INGV has planned the installation of a first offshore buoy with a sea floor pressure sensor in the Ionian Sea in collaboration with EMSO-ERIC (http://emso.eu/). It will use data from a pilot ~20 km SMART seafloor cable (Howe et al., 2019) and pressure sensors connected to deep-ocean observatories located offshore eastern Sicily; both have been funded and are going to be installed in 2022–2023. Once assimilated into CAT-INGV operations, these new instruments will help to reduce the uncertainty associated with tsunami characterization (Angove et al., 2019). Until then, only post-alert tsunami detection at coastal tide-gauges will remain possible.

The last point that is worth mentioning is that the TSPs are not yet fully interoperable. This leads inevitably to different tsunami alert levels being issued by the different TSPs for the same seismic event, as it happened recently in the NEAM region (e.g., Kos-Bodrum, 2017; see Amato, 2020). An effort coordinated by a Task Team appointed by the ICG/NEAMTWS is currently underway to improve the interoperability among the TSPs, starting with a web service providing the official version of the fundamental databases to all of them (e.g., http://t.ly/Mmc0).

3. Legislation, guidelines, protocols, and standard operating procedures

In the NEAMTWS framework, CAT-INGV, the Italian TSP, acts also as National Tsunami Warning Centre (NTWC) and Tsunami Warning Focal Point (TWFP), while DPC (Dipartimento della Protezione Civile; Civil Protection Department) holds the role of Tsunami National Contact (TNC). In 2016, CAT-INGV was accredited by the ICG/NEAMTWS as an official Tsunami Service Provider together with the other candidate TSPs of France, Greece, and Turkey. Portugal followed them in 2019. The accreditation procedure was conducted for each TSP by a panel of experts appointed by the Steering Committee of the ICG/NEAMTWS. The panel evaluated the Standard Operational Procedures (SOP) that CAT-INGV established in the previous years, while it was acting as a candidate TSP.

In Italy, CAT-INGV is embedded in the SiAM (Sistema di Allertamento nazionale per i Maremoti generati da sisma; which means national alerting system for earthquake-induced tsunamis), composed by ISPRA, DPC, and INGV. Hence, CAT-INGV operates under the aegis of UNESCO and according to the mandates of a Prime Minister Directive (DirPCM, 2017), which formally establishes the SiAM, and identifies the roles of DPC, CAT-INGV and ISPRA in the tsunami warning system.

According to the DirPCM (2017), CAT-INGV operates 7 days a week, 24 h a day, in the seismic monitoring room of INGV, based in Rome (Figure 2); it is responsible for assessing the tsunamigenic potential of the recorded seismic event and to provide the alert level and the expected tsunami arrival time at given forecast points along the coast. Moreover, CAT-INGV constitutes the scientific information source of SiAM, providing earthquake and tsunami assessment, and tsunami forecasting in real time. ISPRA manages the Italian National sea level Network (Rete Mareografica Nazionale, https://www.mareografico.it/) and hosts on its website the inundation maps for the Italian coasts (http://sgi2.isprambiente.it/tsunamimap/). DPC has the task of coordinating the SiAM and is in charge of the alert dissemination.

3.1. Legislative and procedural gaps, and remedies

The DirPCM (2017) stresses that CAT-INGV operations must refer to the guidelines developed by the ICG/NEAMTWS as well as to all those which, although developed for other ICGs, may present elements of scientific and operational interest that can be applied at national level. It is worth mentioning the Global Service Definition Document (UNESCO-IOC, 2016), providing useful indications on all the components of TWSs, and a Manual containing Plans and Procedures for Tsunami Warning and Emergency Management (UNESCO-IOC, 2017b). Following the publication of the DirPCM (2017), a reorganization of the CAT-INGV governance, structure, and internal procedures (staff on duty, on call, etc.) became necessary to be aligned with both the international and the renewed national landscapes. The international documentation by UNESCO-IOC (2016; 2017b) has been used as a guideline, with specific integrations for the Mediterranean basin and taking into account the prescriptions of the DirPCM (2017). On the other hand, CAT-INGV is contributing to the definition of a new generation of NEAM documents, including the Strategic Plan for 2021–2030, the TSP Operational User Guide, and an Implementation Plan; the participation to the process of production of the international guidelines helps to avoid incompatibilities and facilitates the establishment of coherent procedures at the national level.

A major challenge is represented by the fact that each TSP operates following rules, using hardware and software,

Figure 2. The INGV 24/7 seismic surveillance and CAT-INGV monitoring room.

personnel, etc. that are different from any other TSP. This is due to different preexisting structures and organizations of the monitoring services and more in general to the different national legislations. Therefore, the protocols and job descriptions of each TSP/NTWC need to be very specific, clear, and easily comprehensible by all the personnel involved in the surveillance. As a drawback and due to the lack of strict operational rules, these peculiarities may add up with some technical differences (see Section 2.1), thus contributing to limiting the interoperability among the TSPs.

The documentation represents an essential aspect to guide staff on duty and senior researchers on call in the correct management of alerts but also to codify the shared scientific and technical standards, updated to the best science and experience of the historical moment, and explaining the limits of the service. For this reason, they can also help to define and limit in turn the responsibility of scientists and technicians involved in the service. In the Italian legal system, in fact, the compliance with scientifically accredited guidelines and protocols helps to justify a decision, which may have caused damage, and, thus, limit or eliminate the liability of the person who acted. CAT-INGV, together with the other SiAM members, is conscious of the importance of these documents and has started a procedure to adopt them.

This complex process envisages the issuance of the following set of documents, some of which have been already finalized:

a) The job description documents for personnel on duty and for experts on-call (CAT-INGV SOP). They clarify the procedures for the alert and provide clear procedural and behavioral lines during a tsunamigenic earthquake; they also include checklists. As a result of the collaboration among CAT-INGV steering committee members, staff on duty and senior researchers on call, the job descriptions for both these functions have been defined in 2017 and have been recently updated. A new version of the CAT-INGV SOP is presently under revision for publication within the end of 2021.

b) The CAT-INGV protocol, which is being drafted by the CAT steering committee members. It adopts the model indicated in the Plans and Procedures for Tsunami Warning and Emergency Management (UNESCO-IOC, 2017b). This protocol will be the complete guide for all operational procedures of the CAT-INGV. It will be released by early 2022.

c) The joint protocols between CAT and DPC and between CAT and ISPRA were prepared by all involved parties. They define the respective duties and the communication standard procedure. INGV and DPC signed the joint protocol in 2020, which is now being updated based on the experience of the last two years. The joint protocol with ISPRA is still under discussion. It will be released by early 2022.

All of these documents will undergo a review and validation process by an external collective national scientific body (such as the Major Risks Commission). Significant modifications of the SOPs with respect to the one used for the CAT-INGV accreditation at the ICG/NEAMTWS in 2016 will be communicated to the ICG and possibly validated by an international expert panel. It is the case for example of the transition from the DM to the PTF described above (2.1).

4. Hazard modelling and inundation mapping across scales

CAT-INGV is involved in the national tsunami hazard mapping coordinated by DPC, and its activity relies upon documented scientific experience (Grezio et al., 2017; Behrens et al., 2021, and references therein), and collaborations within a broad international scientific network, as testified by the active participation in the construction of the Global Tsunami Model (GTM; www.globaltsunamimodel.org), the involvement in the AGITHAR Cost Action (https://www.agithar.uni-hamburg.de/) with the associated special issue (Lorito et al., 2021), the participation in GAR activities (e.g., Gordon et al., 2019; Løvholt et al., 2019), and the coordination of the TSUMAPS-NEAM project (http://www.tsumaps-neam.eu/) among other research projects (e.g., ASTARTE, http://www.astarte-project.eu/). Scientific networking activities served to establish community standards for Probabilistic Tsunami Hazard Analysis (PTHA), partly derived from the longer established seismic hazard analysis (e.g., Geist and Parsons, 2006).

INGV researchers have conducted several PTHAs at different scales, from the global (Davies et al., 2017) to the regional (NEAMTHM18; Selva et al., 2016; Basili et al., 2021) and to the very local scale, but, in this case, it was for methodological purposes only (Lorito et al., 2015; Volpe et al., 2019). Most of them have been formally endorsed by CAT-INGV or funded in the framework of the agreement between INGV and DPC.

The inundation maps for the Italian coastlines included in the Civil Protection recommendations for the update of local Civil Protection plans (DPC, 2018) are based on the NEAMTHM18 regional-scale PTHA. Inundation heights with an average return period of 2500 year were extracted from this PTHA model, considering the 84th percentile of the epistemic uncertainty; then, a chain of cautionary choices, combined with a GIS-based procedure for projecting maximum inundation heights onto inundation distances, were applied to define the inundation zones to guide local authorities in the development of civil protection planning (Tonini et al., 2021).

4.1. Gaps in hazard modelling and inundation mapping, and remedies

It has to be noted that inundation in the NEAMTHM18 PTHA model is computed with approximated methods, rather than via numerical hydrodynamic inundation simulations, due to the large number of sources and to the extent of the region. Exploring both aleatory and epistemic uncertainty in NEAMTHM18 involved indeed the numerical simulation of millions of scenarios. It was then deemed necessary to limit the computational cost recurring to linear combinations of precomputed tsunamis waveforms from "unit" sources (Molinari et al., 2016), picked at the 50 m isobath, and using a stochastic modelling approach based on amplification factors to estimate the distribution of inundation heights for each tsunami scenario (Glimsdal et al., 2019). The multi-GPU finite volume Tsunami-HySEA code (Macias et al., 2017) and the availability of computational resources on CINECA supercomputers (https://www.cineca.it) permitted to run tens of thousands of tsunami scenarios on a relatively large domain such as the NEAM region sampled at 30 arc-sec spatial resolution. Additionally, at the time of these calculations, we had to limit the spatial sampling along the coast to ~20 km, to limit the total size of necessary disk space and the computational time needed for post-processing and hazard aggregation. Besides, the seismic crustal source treatment was simplified by adopting uniform earthquake slip for each scenario equal to the value prescribed by the empirical scaling relations, rather than using several realizations of a heterogeneous slip distribution, which may affect the inundation pattern, particularly in the near-field (e.g., Tonini et al., 2020; Serra et al., 2021).

Another (typical) reason for adopting the stochastic approach for inundation modelling is the difficulty to find accurate and high-resolution topographic-bathymetric models that continuously cover the offshore-onshore transition along the coastal zone. For example, due to the objective difficulty in surveying very shallow waters, high-quality bathymetric models like EMODNET (https://emodnet.ec.europa.eu/en/bathymetry) miss the connection with the coast in many places.

More recently, in collaboration with NGI (Norway), University of Malaga (Spain), and CINECA, we have set up a workflow based on massive simulations of large ensembles of tsunami scenarios, in the framework of the ChEESE project, which is aimed at the constitution of a Center of excellence for the (future) Exascale computing for solid earth (https://cheese-coe.eu/). With the HPC-based workflow, we can now afford local inundation studies at the spatial resolution of 5–10 m while still considering tens of thousands of simulations (e.g., Gibbons et al., 2020). Thanks to the resources available on several Tier-0 PRACE supercomputers across Europe (https://prace-ri.eu), including Marconi100 at the Italian HPC centers at CINECA (https://www.cineca.it/en/hpc; Figure 3) and HPC5 at the ENI HPC centre (https://www.eni.com/en-IT/operations/green-data-center-hpc5.html), we first calibrated and then executed the workflow to compare the approximate methods used for the national inundation maps with high-resolution simulations (Tonini et al., 2021). We evaluated the reliability of the approximations

Figure 3. The Tier-0 GPU-based supercomputer Marconi100 of the CINECA HPC center.

and quantified the extent of conservatism chosen by the authorities, with the CAT-INGV guidance, mostly based on expert judgement. The results were satisfactory, taking into account that the numerical simulations are affected by uncertainties as well. We are presently addressing such uncertainties with an ongoing sensitivity analysis of about ten millions high-resolution scenarios at about ten coastal sites in the Mediterranean. The lessons learned from this numerical experiment -- unprecedented in this context -- will be used during the finalization of the next generation of national PTHA, which will be submitted for evaluation at the beginning of 2022.

Classic PTHA evaluates the probability of exceeding a given hazard intensity at a given location in a given future time interval. It does not account for the arrival time or the hydrodynamic characteristics of the many scenarios concurring to the hazard. For example, the risk associated with a distant tsunami, especially in the presence of a tsunami warning system, is lower than that from a local tsunami hitting only a few minutes after the earthquake origin time. Several groups are starting to consider these additional hazard dimensions (e.g., Wood et al., 2020; Zamora et al., 2021), and we have begun to address the issue in view of future updates of national PTHA.

Nonetheless, we should also note that we have not addressed yet tsunami hazard from nonseismic sources (Selva et al., 2021a) and that, even for seismic sources, we deal with relatively rare events; hence, their temporal characterization is necessarily affected by large uncertainty (Behrens et al., 2021).

It is also true that coastal planning is presently based on separate single-hazard assessments and on hazard rather than on risk, with the exception of some critical infrastructures as, for example, those subjected to the EU Seveso Directive for the prevention of major industrial accidents, including those potentially triggered by natural hazards. INGV, ISPRA, and ReLUIS (Network of the University Laboratories of Seismic Engineering), under the coordination of DPC, are working on a feasibility study regarding the realization of a national tsunami risk assessment for several construction types and life losses.

One complementary aspect is the need to ensure that the products that are relevant for science but also for risk assessment and management are FAIR (https://www.go-fair.org/fair-principles/) and are distributed within a sustainable framework. For this reason, CAT-INGV has been endorsing from its very conception about 5 years ago, the creation of the Thematic Core Service (TCS) “Tsunami”, which has now reached the official status of candidate TCS in EPOS-ERIC (https://www.epos-eu.org/). Among the INGV products envisaged for inclusion in the TCS Tsunami service provision, there are historical and paleotsunami catalogues and the NEAMTHM18 hazard model.

5. Tsunami warning last-mile

It is well known that the defence from tsunami risk needs well informed and well aware citizens (e.g., UNISDR, 2015). Most of the work in the past 15 years has been focused on the so-called "upstream" component of the NEAMTWS: the optimization of seismic and sea level networks for tsunami monitoring, the creation of a coordinated system of TSPs and NTWCs able to provide tsunami forecasts, issue alert messages, and monitor the sea level. As experienced in some recent tsunamis (e.g., Papadopulos et al., 2020; Dogan et al., 2021), one critical issue of the NEAMTWS is filling the so-called last mile, that is, raising awareness about the tsunami risk, preparing emergency and long-term coastal planning, and reaching the people at risk with the alert messages (e.g., Amato, 2020).

Since 2011, the Civil Protection Department, in collaboration with INGV, ANPAS (Public Assistance Italian Associations), CIMA (International Center for Environmental Monitoring), and ReLUIS (Network of the University Laboratories of Seismic Engineering), and with the support of several Italian regions and municipalities, has promoted the national campaign named "Io non rischio" (http://iononrischio.protezionecivile.it/en/homepage/), which means "I don't take risks". It is an itinerant communication and awareness raising campaign on best practices of civil protection, carried out in the squares and meeting places of Italian municipalities at risk of earthquakes, tsunamis, volcanoes, and floods.

Interaction and collaboration among the SiAM members, in recent years, allowed paying increasingly more attention to the "downstream" component: the system part that translates and links the upstream analysis of a tsunamigenic event to the actions to be taken by the actors involved in the emergency management (Civil Protection, Volunteers, Firefighters, Police, etc.) contributing to risk mitigation. For this reason, the SiAM, as a whole, participated actively in the organization and execution of the NEAMWave exercises held in 2017 and 2021 (UNESCO-IOC, 2021; Figure 4). These exercises have a two-fold purpose. On the one hand, they are meant to raise awareness regarding both the tsunami risk and the NEAMTWS existence; on the other hand, they serve to test the warning message transfer mechanisms, the "warning chain", down to the regional and local authority level. They require direct collaboration between CAT-INGV, ISPRA, and DPC but also some Regional Civil Protection authorities and some municipalities, with whom also other table-top activities were carried out in 2019 and 2020. In 2021, some municipalities involved in achieving UNESCO "Tsunami Ready" recognition (e.g., Minturno, in the Lazio Region, see Section 5.1) organized field exercises.

CAT-INGV has also focused on two additional tasks, namely i) the study of tsunami risk perception (Cerase et

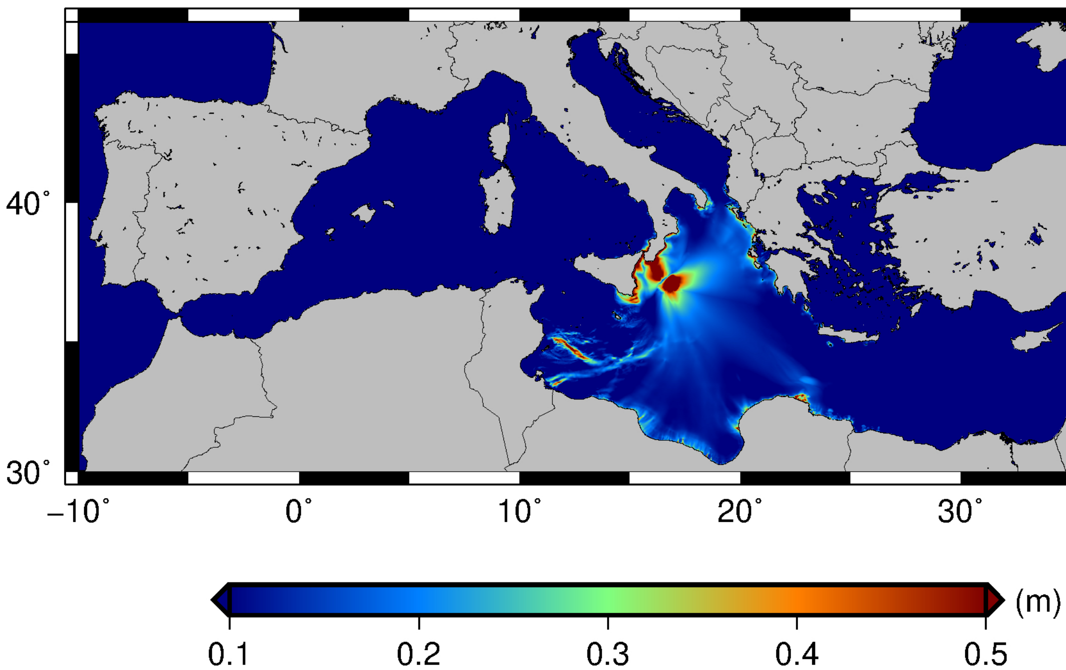

Figure 4. Maximum tsunami wave amplitude distribution for the scenario proposed by INGV during the NEAMWave21 exercise. The tsunami source (earthquake with magnitude M_w7.9) was located along the subduction interface of the Calabrian Arc (Figure modified after UNESCO-IOC, 2021).

al., 2019; Cugliari et al., 2021), ii) the development of a dedicated website (www.ingv.it/cat), and iii) the creation of informative material.

Scientists base risk studies on objective and subjective criteria (Slovic, 2000). As such, different types of natural hazards that characterize the Mediterranean context need to be approached in a framework that considers risk also as a social construct (Neaves et al., 2017). Previous studies on tsunami risk perception had been carried out in the NEAM region during the EU-funded project ASTARTE (http://www.astarte-project.eu/). In this regard, the CAT-INGV has promoted the pilot survey on tsunami risk perception in Italy. This study, conducted between 2018 and 2021, surveyed 5842 citizens living in the 450 coastal municipalities (Figure 5). This stratified sample is representative of approximately 10 million people living along the Italian coasts. The most recent survey (2021) also collected 1500 interviews from a nationwide public of a selected sample (Telepanel). The main purpose of the survey is to derive useful indications for improving scientific communication, to help stakeholders to implement focused intervention policies, for designing activities that increase population preparedness, and for setting up effective emergency communication strategies. The questionnaire structure allows for full or partial application in other geographical contexts, in the NEAM area and internationally (see Supplementary material in Cerase et al., 2019). The CAT-INGV website (www.ingv.it/cat) provides a repository of information on tsunami hazard and risk, on monitoring and alerting activities, on how to behave to defend from tsunamis, and so on. The website contains regularly updated information about tsunamis worldwide, ongoing alerts in the NEAM region and in other ICGs, new projects and publications, campaigns, etc. Particular attention has been given to the continuity of information, with the release of news approximately every week. Since 2 May 2020, the date in which the website went online, under the "pressure" of the

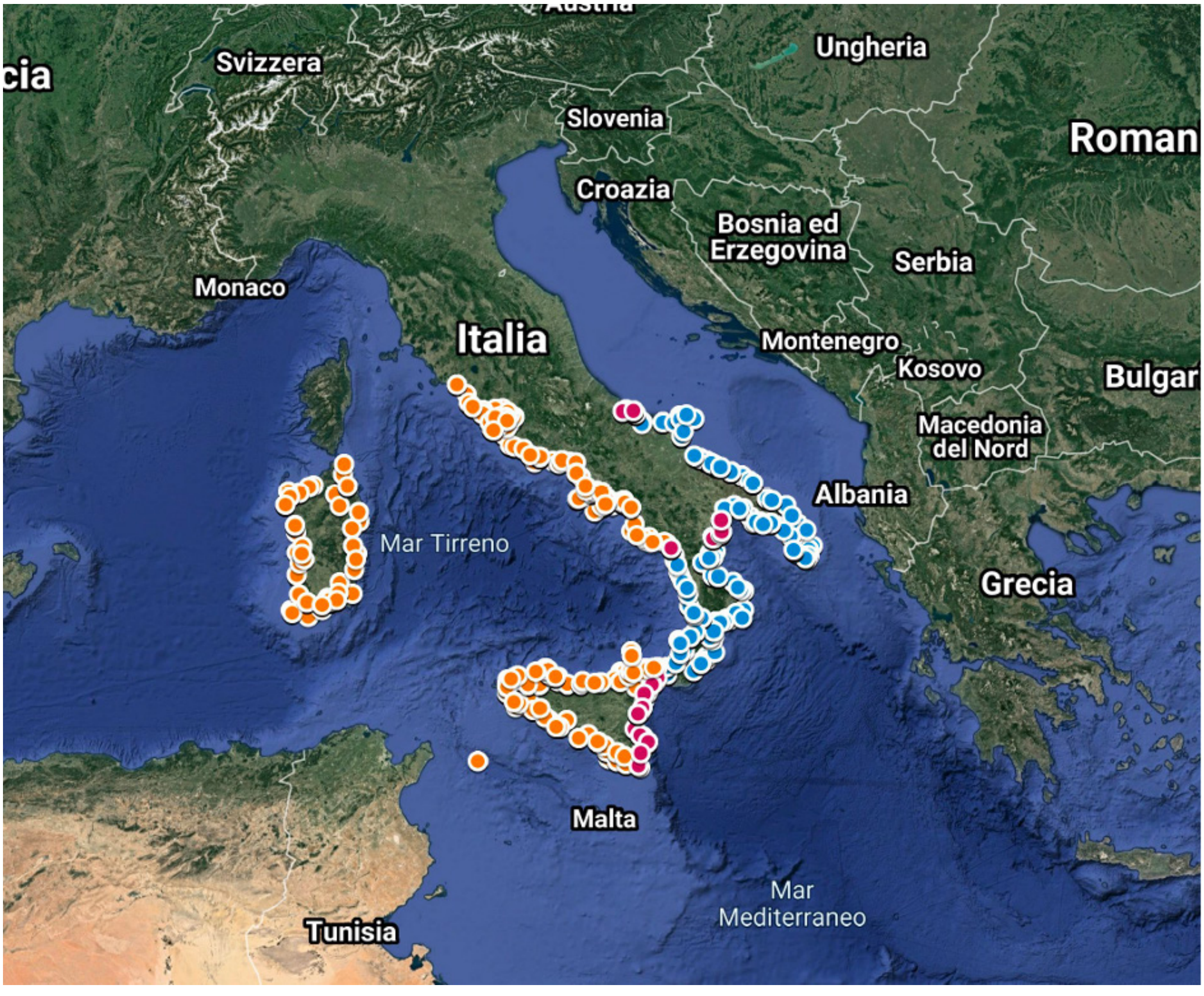

Figure 5. The distribution of tsunami risk perception interviews in Italy. The three phases of the survey are identified with different colours: blue for the first phase (2018), red for the second phase (2019), orange for the third phase (2021).

M_w6.6 earthquake in the Cretan Passage, south of Crete, Greece, which caused a moderate tsunami in the nearby location of Ierapetra (Baglione et al., 2021), 56 news articles were published (Figure 6). The website is linked with other tsunami-related websites, such as the NEAMTIC website, the official Tsunami Information Centre of the NEAM area (http://neamtic.ioc-unesco.org/). CAT-INGV personnel also contributes to the broader INGV communication activities (e.g., https://ingvterremoti.com/), with multimedia, textual, and infographic contents oriented toward informing and increasing citizen awareness (e.g., https://ingvterremoti.com/libro-terremotimaremoti/, t.ly/sxN4; https://youtu.be/ACgLCA-BJL4).

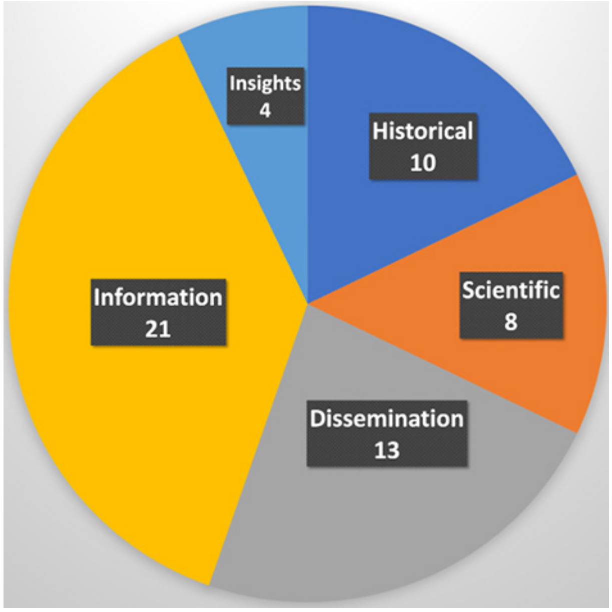

Figure 6. Thematic distribution of the items published on the CAT website news section (https://www.ingv.it/cat/en/media-and-documents/news-en) since the opening of the website on 2 May 2020, following the M_w6.6 Cretan Passage earthquake and the ensuing moderate tsunami.

5.1. Gaps in the last-mile, and remedies

Despite all the progress made, as described in the previous Sections, in Italy, and as far as we know in many other NEAM countries, the alert messages sent by the TSPs/NTWCs can automatically and immediately reach all the operational structures at the national and territorial level of the Civil Protection system (including all the local authorities; a number of institutions providing mobility, telecommunications, and other essential services), but not yet the general population. DPC has been working on the IT-Alert project (https://www.it-alert.it/), a public alert system to reach citizens directly, composed of three elements: cell broadcasting technology, an app for smartphones, and dedicated web services. This system will deal with different types of alert messages, for example meteo alerts, not only tsunami ones; it will undergo a testing phase and then become operational.

Another ongoing activity (a gap, then, for the time being) regards the updating of local emergency plans. Italian coastal municipalities are required to update their emergency plans with the inclusion of the tsunami risk, based on the guidelines by the Civil Protection Department (DPC, 2018). We notice that no additional funding for municipalities was allocated to this task, and that to date, only a few of them have reached this objective. Their tasks include the implementation of the evacuation zones and plans, the development of infrastructures to disseminate the alert messages to the population such as sirens, and the installation of tsunami signs, which would assist people during the evacuation.

Some of these tasks could be better addressed through the direct involvement of local authorities and citizens in the risk governance issues. A powerful tool to achieve the preparation, in a broad sense, of the coastal communities through an integrated approach involving all the relevant actors and stakeholders is the Tsunami Ready program (https://ioc.unesco.org/our-work/tsunami-ready-pilot-programme). For this reason, in 2020, the adoption of Tsunami Ready was promoted by CAT-INGV and DPC as a tool to increase awareness and preparedness in Italy. In 2020, the program started in three pilot sites in Italy, exposed to low-to-high tsunami hazard: Minturno (Latium; Figure 7), central Tyrrhenian Sea; Palmi (Calabria), southern Tyrrhenian; Marzameni (Sicily), along the Ionian coast of Eastern Sicily. Both Palmi and Marzamemi have been hit by historical tsunamis. In 2021, DPC nominated the National Tsunami Ready Board, whilst the three municipalities deliberated the Local Tsunami Ready Committees, composed of representatives of official bodies (such as the local police, the coast guard, etc.), volunteer associations, and category associations (hotels, campings, etc.). The Tsunami Ready guidelines can be indeed a starting point to solve also some structural lacks of the municipalities (e.g., lack of sirens, warning diffusion on the territory, specific escape routes and gathering points for tsunami, etc.).

6. Discussion and conclusions

As of today, the NEAMTWS has set up an advanced upstream tsunami warning component, which, in our opinion, is scientifically and technologically comparable in many respects to the most advanced ones worldwide (Section 2). We highlight that the accreditation procedure of the TSPs is unique to the NEAMTWS. Yet, we have identified some important gaps in the seismic and tsunami observation coverage -- literally a gap in the azimuthal instrumental coverage --, as well as in the

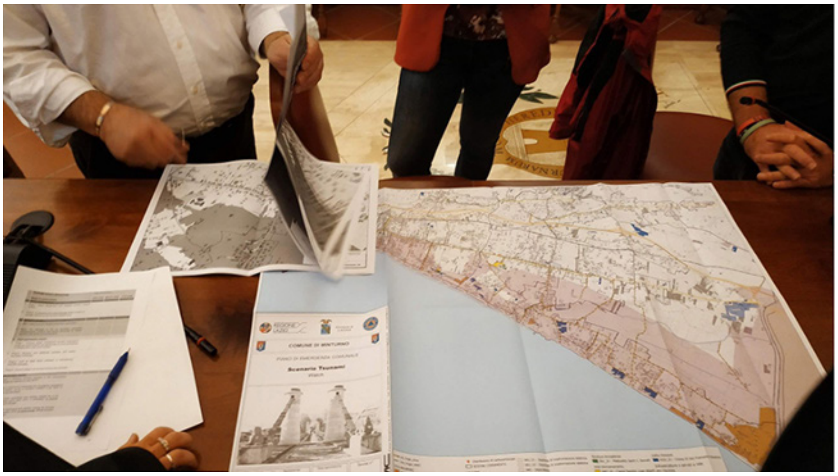

Figure 7. Analysis of the inundation zones to be used for local evacuation planning during a Tsunami Ready meeting with the Local Board of Minturno, Italy.

warning procedures and interoperability of the TSPs. It is nevertheless evident that keeping the current pace of development in the upcoming years will progressively improve the situation. In particular, we wish to emphasize some strong innovations being pursued in the upstream component:

1. The uncertainty quantification in the probabilistic tsunami forecasting as proposed by CAT-INGV has the potential to address in a systematic way the balance between expected false and missed alarms (Selva et al., 2021b).

2. The densification of the instrument networks with the integration of GNSS sensors transmitting in real-time, promoted mainly by NOA and INGV with the support of GFZ and other TSPs, and the installation of new offshore sensors by ISPRA and by INGV in collaboration with EMSO-ERIC, will improve the early tsunami detection and characterization capability at several locations in the Mediterranean Sea.

3. The ICG/NEAMTWS is making an effort for achieving a better interoperability and sustainability of the TSP operations.

Following this analysis of the upstream component of the NEAMTWS, we have been looking mostly at the national scale. We have reviewed the CAT-INGV efforts in the framework of the SiAM towards the creation of a robust formal framework for the rational management of the responsibilities connected to an alert system (Section 3). A snapshot of the current situation has shown that, starting from the accreditation as a TSP and the formulation of a dedicated national legislation, CAT-INGV and the other actors of the SiAM are progressively creating -- from scratch, we may say -- a set of best-practices regarding the procedural, regulatory and legal aspects of the system. This effort includes the following items:

1. The continuous update of the legal and procedural frameworks to remain aligned with the continuous scientific and technological development and with the best practice worldwide.

2. The formalization of independent review procedures aimed at verifying that the tsunami warning operations actually comply with the state-of-the-art science and knowledge.

These activities need to be regarded as structural ones, rather than as occasional updates in response to major changes. The revision process should be continuous, with updates in the procedure to advance at a pace depending on the scientific and technological developments.

However, risk management and reduction activities go much beyond the upstream component of the warning system. For this reason, we have also discussed the hazard and risk assessment and understanding (Section 4). Then, we have touched upon the last-mile of the tsunami warning in the broad sense, which ranges from the operational alert dissemination during an event, to the preparation of the population and the long-term coastal planning.

Following a prolonged interaction with the scientific component of the SiAM, aimed at ensuring a correct communication of the NEAMTHM18 model and of its uncertainty (Basili et al., 2021), the political authority decided that the evacuation maps in Italy should depend on the inundation level with a probability of ~ 2% in 50 years (i.e. with an average return period of 2500 years), adopting the 84th percentile of the model uncertainty, and other precautions (Tonini et al., 2021). Starting from the complete hazard curves DPC could choose, potentially in a broader cost-benefit multi-hazard framework, the desired or accepted level of risk reduction. In our opinion, this is a transparent and virtuous approach, going in the right direction of "risk-informed" planning, and based on the best available PTHA model covering all Italy's coastlines.

Yet, both the hazard model and the overall approach to derive the inundation maps for planning have some limitations. The model takes into account only earthquake-generated tsunamis, which are the majority; the resolution of the PTHA model is limited and inundation modelling is approximated; the planning takes into account only a single hazard, and the hazard rather than the risk. To move forward, CAT-INGV is now participating in several projects and activities dealing with, for example

1. HPC-based high-resolution PTHA with full uncertainty estimation (Gibbons et al., 2020),

2. A feasibility study for a national tsunami risk map, in collaboration with ISPRA and ReLUIS under the coordination of DPC,

3. A review of non-seismic sources and on the status of the planning to deal with them in Italy (Selva et al., 2021a), and the active participation in the AGITHAR COST Action, to draw consensus guidelines for tsunami risk assessment (Behrens et al., 2021).

Last but not least, CAT-INGV is strongly involved in a number of activities related to the implementation of the last-mile of the warning system (Section 5). It is true that the last-mile still needs a lot of attention to be really implemented. First of all, to finalize the infrastructure and the tools that are necessary for the alert messages to reach the population under the tsunami threat. But a community can properly use the technological support during an emergency if it has received appropriate training and is aware of the risk and of the emergency procedures. Otherwise, the technological medium could create counterproductive and harmful effects. Keeping citizens adequately informed, aware, and ready to face a tsunami threat is a very difficult task to achieve because tsunamis are infrequent compared to other phenomena, and most people tend to be insensitive to risk education if not involved directly; hence, the risk is generally underrated and the populations underprepared. This implies that also the (national to local) authorities may see the planning activities for tsunami risk management as less urgent than those related to other risks (e.g., seismic, meteorological), which may be considered as more imminent as they occur more frequently. Despite these difficulties, the SiAM is strongly engaged in numerous activities, such as:

1. Risk communication and awareness raising, through campaigns over the Italian territory (http://iononrischio.protezionecivile.it/en/homepage/), or via institutional websites (www.ingv.it/cat),

2. Studies on risk perception to better orient risk management strategies,

3. Development of the Tsunami Ready program in pilot sites, which is an integrated and multi-faceted action to improve coastal community preparedness for tsunamis,

4. Realization of the IT-Alert project (https://www.it-alert.it/), a public alert system to reach citizens directly.

From this short but intense journey through the different aspects of tsunami risk management in Italy, it emerges in our opinion that the SiAM -- the Italian national tsunami alert system -- has achieved quite outstanding results, which is also true for, and would have been impossible without, the NEAMTWS as a whole. This is particularly impressive considering that tsunamis are often categorized as low-frequency, high-consequence natural phenomena; it is even more the case in the NEAM region, where tsunamis are less frequent than for example in the Pacific Ocean. Nonetheless, with the aim of operating a feedback mechanism from inside to calibrate the future efforts, we have identified several gaps. We have also highlighted that the SiAM at the national level and the NEAM at the transnational level, keep producing an intense, long-standing effort for filling these gaps, towards an improved management of the tsunami risk.

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