Scenario-based tsunami hazard assessment for Northeastern Adriatic coasts

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Abstract
Significant tsunamis in the Northern Adriatic are rare, and only a few historical events have been reported in the literature, with sources mostly located along central and southern parts of the Adriatic coasts. Recently, a tsunami alert system has been established for the whole Mediterranean area; however, a detailed description of the potential impact of tsunami waves on coastal areas is still missing for several sites. This study aims to model the hazard associated with possible tsunamis generated by offshore earthquakes, with the purpose of contributing to tsunami risk assessment for selected urban areas along the Northeastern Adriatic coasts. Tsunami modelling is performed by the NAMI DANCE software, which allows accounting for seismic source properties, variable bathymetry, and nonlinear effects in wave propagation. Hazard scenarios at the shoreline are developed for the coastal areas of Northeastern Italy and at selected cities (namely, Trieste, Monfalcone, Lignano and Grado). An extensive set of potential tsunamigenic sources of tectonic origin located in three distance ranges (namely at Adriatic-wide, regional and local scales) are considered for the modelling. Sources are defined according to available literature, which includes catalogues of historical tsunamis and existing active faults databases. Accordingly, a set of tsunami-related parameters and maps are obtained (e.g. maximum run-up, arrival times, synthetic mareograms) that are relevant to planning mitigation actions at the selected sites.

Keywords Tsunami hazard assessment · Northern Adriatic Sea · Tsunamigenic earthquake · Aggregated scenario

1 Introduction

The coastal areas of the Adriatic Sea are exposed to a range of natural hazards, including floods, windstorms, droughts, earthquakes, and tsunamis. Although strong tsunamigenic earthquakes are not frequent in the Adriatic Sea, their impacts could be considerable given the coastal exposure and vulnerability. Indeed, even a moderate tsunami may have a relevant effect on some areas due to the presence of sites of high historical/cultural/touristic interest (e.g. the city of Venice) and fragile ecosystems (e.g. lagoons and river deltas). Defining hazard scenarios for a wide range of possible tsunamigenic earthquakes is essential to reduce their potential socioeconomic impacts on coastal communities and set up

sustainable development plans for inland and offshore areas. The adequate estimation of expected hazards, along with the characterization of exposed assets and their vulnerability, provides the basis for tsunami risk assessment.

Historical records indicate that the Adriatic region experienced considerable impacts from earthquakes and tsunamis in the past (Papadopoulos et al. 2014; Maramai et al. 2014; 2019; 2021). For instance, the 30 July 1627 Gargano earthquake (M_w6.7) and subsequent tsunami caused widespread destruction along the Eastern Adriatic coast (Patacca and Scandone 2004). More recently, the 15 April 1979 Montenegro earthquake (M_w6.9) generated a local tsunami that affected the coastal areas in Montenegro and Albania. Overall, Pasarić et al. (2012) identified 27 tsunamigenic events that occurred during the last 600 years: 9 of them are located on the west side of the Adriatic Sea, while 18 along its eastern side (6 are classified as reliable and 10 as unreliable, while 2 are categorized as events of meteorological origin). In 2019, an updated tsunami catalogue for the Mediterranean region was published, namely, the Euro-Mediterranean Tsunami Catalogue (EMTC), which includes a detailed survey

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of tsunamis of seismic origin in the Adriatic Sea (Maramai et al. 2019). This study identified the potential tsunamigenic events, including a level of uncertainty in the location and magnitude of seismic events.

Significant tsunamis are rare in the Northern Adriatic, where only a few historical events have been reported in the literature, with sources mostly located along the central and southern parts of the Adriatic coasts (Maramai et al. 2007; Tiberti et al. 2008). Based on historical information, recent review studies support the relevant impacts of past tsunamis in the Northeast Adriatic region in 1348 and 1511 (Maramai et al. 2021). Despite the evidence of sporadic but possibly damaging events, a detailed investigation of the potential impact of tsunamis of seismic origin on coastal activities and communities along the Northern Adriatic coasts is still unavailable. Therefore, this work aims to provide different scenario-based tsunami hazard metrics along the shoreline for the area of interest (e.g. maximum wave amplitude, estimated time of arrivals) given the available source, bathymetry and topography datasets. The results are essential for a comprehensive understanding and assessment of exposure, vulnerability and risk, thus for increasing the resilience of coastal communities in the Northeastern Adriatic region. Moreover, these results are also needed to develop emergency plans, as well as to suitably inform residents and visitors about the potential tsunami risk in the region and to convey adequate instructions in the event of a tsunami warning.

Recently, a tsunami early warning system has been established for the entire Northeast Atlantic and the Mediterranean region, referred to as NEAMTWS (Tsunami Warning and Mitigation System in the Northeastern Atlantic, the Mediterranean and connected seas). In this framework, the CAT-INGV system (Centro Allerta Tsunami, https://cat.ingv.it/en/), managed by INGV (National Institute of Geophysics and Volcanology), operates as a tsunami warning centre for the entire Mediterranean, including the Adriatic Sea (Amato et al. 2021). At the national level, CAT-INGV operates within the formal framework of the National Alert System for Earthquake-Generated Tsunamis (SiAM—Sistema Allertamento Maremoti), established in 2017 (Directive of the President of the Council of Ministers, 17 February 2017) to disseminate tsunami alert messages to the territory, including local authorities. A debate is ongoing about the possibility of delivering *last-mile* messages to alert the population (Papadopoulos et al. 2020). In case a potential tsunamigenic event occurs, the system provides alert messages expressed by the following three levels, in order of increasing severity: "information" (green), "advisory" (orange) and "watch" (red), based on the specific decision matrix (Fig. 1) reported in Amato et al. (2021). According to this matrix, the distance between a site of interest and the epicentre is divided into three possible categories: local

Depth	M	Epicenter Location	Tsunami Potential	ALERT LEVEL *VS* DISTANCE		
				Δeq ≤ 100 km	100 km < Δeq ≤ 400 km	Δeq > 400 km
< 100 km	5.5 ≤ M ≤ 6.0	Offshore or Inland ≤ 100 km	Nil	Information Bulletin		
	6.0 < M ≤ 6.5	Inland (40 km < Inland ≤ 100 km)	Nil	Information Bulletin		
		Offshore or near the coast (Inland ≤ 40 km)	Potential of weak local tsunami Δeq < 100 km	LOCAL Tsunami ADVISORY	Information	
	6.5 < M ≤ 7.0	Offshore or Inland ≤ 100 km	Potential of destructive local tsunami Δeq < 100 km | 400 km	LOCAL Tsunami WATCH	REGIONAL Tsunami ADVISORY	Information
	7.0 < M ≤ 7.5		Potential of destructive regional tsunami Δeq < 400 km | basin	REGIONAL Tsunami WATCH		BASIN-WIDE Tsunami ADVISORY
	M > 7.5		Potential of destructive tsunami in the whole basin any Δeq	BASIN-WIDE Tsunami WATCH		
≥ 100 km	M ≥ 5.5	Offshore or Inland ≤ 100 km	Nil	Information Bulletin		
any	any	Inland > 100 km	Nil	Nil		
				LOCAL	REGIONAL	BASIN-WIDE

Fig. 1 CAT-INGV tsunami decision matrix (https://cat.ingv.it/en/tsunami-alert/alert-procedures/decision-matrix, last accessed May 2023)

(distance $\leq$ 100 km), regional (100 km < distance $\leq$ 400 km) and basin-wide (distance > 400 km). The "*watch*" level is defined when seismic information indicates that the coast may be hit by a tsunami with a wave amplitude greater than 0.5 m offshore (along 50 m isobaths) and/or when the tsunami run-up at the shoreline is expected to be greater than 1 m. The "*advisory*" level is indicated, instead, when the run-up is expected to be less than 1 m. Since 2017, several tsunamis have been located and assigned a watch alert level by the CAT-INGV system, including the Aegean Sea earthquake in 2017 ($M_w = 6.6$) and the more recent events in Crete (2nd May 2020), Aegean Sea (30th October 2020), Northern Algeria (18th March 2021) and the Turkey earthquakes (6th February 2023).

A still open challenge is to go beyond the alerts issued by the early warning system and define detailed impact scenarios that allow evacuation plans and mitigation strategies to be developed with local authorities (e.g. civil protection and municipalities). Such strategies require knowledge of the local context and a detailed definition of hazard/risk scenarios compatible with the potential tsunamis that may affect the region under consideration. Recent studies have been conducted for the Heraklion City, Crete (Triantafyllou et al. 2019) as well as for Southern Italy, both on expected inundation assessment (Tonini et al. 2021) and tsunami risk perception (Cerase et al. 2019). The study conducted by Tonini et al. (2021) focused on two locations along the Eastern coast of Sicily, namely Catania and Siracusa. Their research specifically examined the local tsunami hazard in these areas. To assess the hazard, they used an enhanced digital terrain model (DTM) with a spatial resolution of 10 m for the tsunami simulations. This DTM was created by combining and resampling various raster datasets with different horizontal cell resolutions.

Additionally, for the land portion of the study area, they incorporated a raster dataset with a 1-m cell resolution obtained from the Geology and Geotechnologies Laboratory at INGV, specifically near the coastal zone. However, similar research has not yet been carried out for the Northern Adriatic, where the bathymetric and topographic settings are substantially different. The available tsunami hazard estimates (e.g. NEAMTHM18 maps, Basili et al. 2019), in fact, are provided for sites located along the 50 m depth isobaths; given the very shallow bathymetry of the Northern Adriatic, these sites are very far from the areas of interest (Fig. 2), at a distance of more than 100 km from the coastline (e.g. Amato et al. 2021 and references therein). Usually, to calculate the *run-up* to the coastline (i.e. the maximum topographic height, compared to the mean sea level, reached by the tsunami wave during its ingression), an empirical coefficient (i.e. a multiplication factor) is applied to the maximum amplitude of the tsunami wave estimated along the 50 m isobaths (Tonini et al. 2021). However, in the

Northern Adriatic, the distance between these isobaths and the coastline is very large, and such an empirical relationship may prove inadequate. In addition, in the alert messages, a minimum wave amplitude (or a run-up) level is given for the area of interest, but an upper bound is not provided. According to the mentioned SiAM directive (see Attachment 1 of the directive), the accuracy and reliability of inundation data can be significantly improved at a local scale (e.g. municipal level and port areas), especially for those areas particularly critical due to the presence of strategic infrastructure, high population density, etc., where it is appropriate to integrate its results with detailed studies through physical–numerical modelling. Accordingly, this study aims to provide a more complete and detailed description of the tsunami hazard, following a multi-scenario approach, for specific locations along the northeastern coast of the Adriatic Sea, namely, the cities of Trieste, Monfalcone, Grado and Lignano (Fig. 2), hereinafter referred to as areas of interest (AOI).

The urban centres selected as AOI for this study (Fig. 2) represent important economic, historical and cultural centres. Trieste, the largest city in the Friuli Venezia Giulia Region (FVG), is of fundamental economic importance due to the presence of ports and other infrastructure, making it a strategic site for trade and tourism and its notable historical relevance. Monfalcone is an industrial site with several shipyards and a textile and chemical production centre. The cities of Grado and Lignano are among the leading Italian seaside tourist centres. Lignano, in particular, is a primary tourist site, reaching a population of several hundred thousand visitors during the summer period; the considerable variability of the population throughout the year makes it an area of particular interest for future tsunami risk assessment. Moreover, between Grado and Lignano there is a large lagoon, characterized by a peculiar and fragile ecosystem, with a high degree of vulnerability, due to its direct connection with the Adriatic Sea basin.

Modelling the hazard associated with possible tsunamigenic earthquakes occurring in the Adriatic Sea is therefore carried out to contribute to tsunami risk assessment and emergency management for the selected urban areas located along the Northeastern Adriatic coasts. This research builds on previous studies (Peresan and Hassan 2022) and aims to update the existing tsunami hazard models for the Northeastern Adriatic coastal cities of Lignano, Grado, Monfalcone and Trieste. Recent results based on the computation of an extensive set of tsunami scenarios are presented, considering the possible sources defined in the most updated database of seismogenic sources; parametric tests are performed to account for seismic source variability. Specifically, this study is accomplished by accounting for the recently updated DISS database of seismogenic sources in the Adriatic Sea, considering different potential tsunamigenic sources of tectonic origin located in three
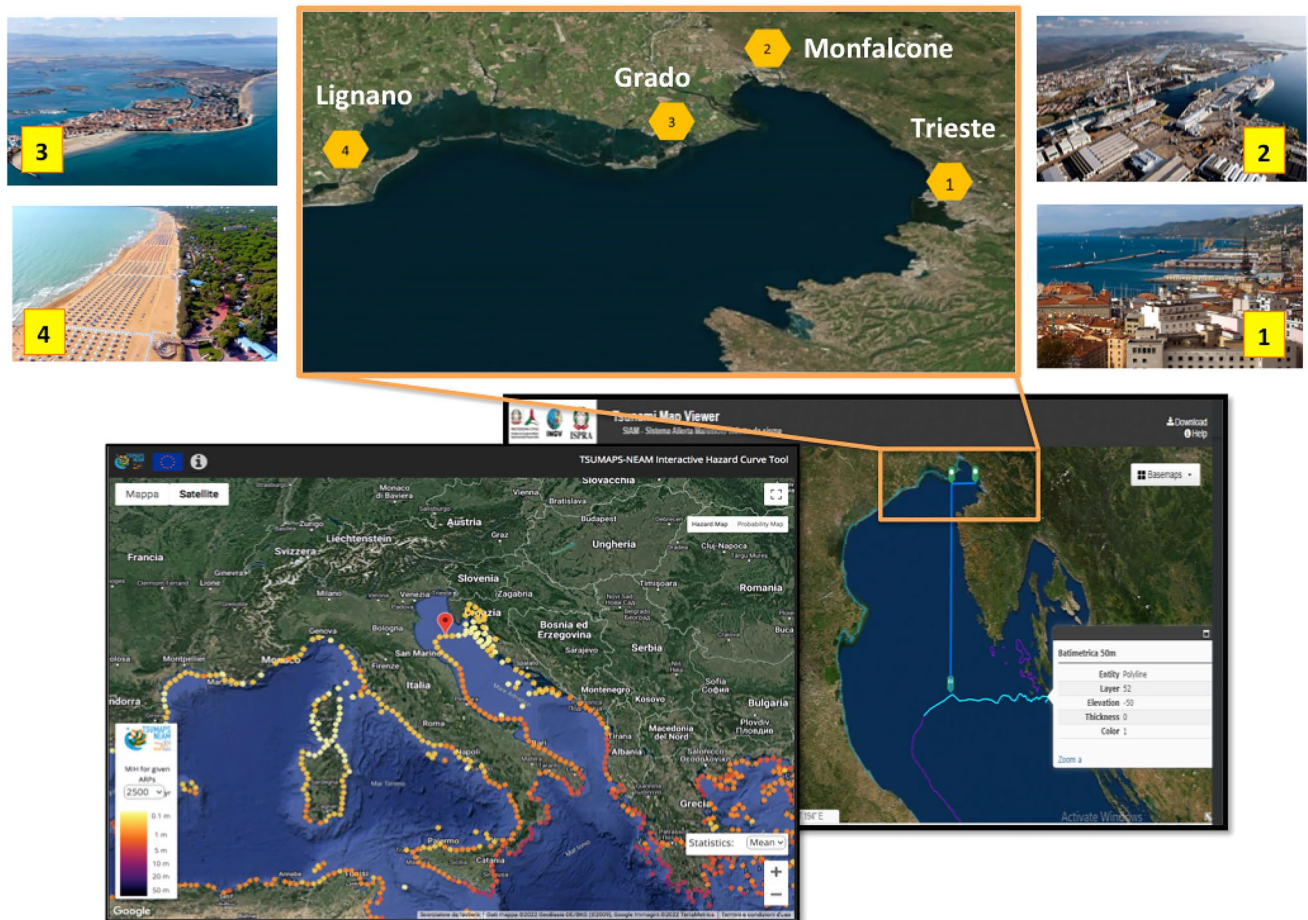
Fig. 2 Regional and zoomed maps of the study region: (top) map of Northeast Adriatic Sea and photos of the areas of interest, AOI; (bottom) map of tsunami hazard estimates for the NEAM macro-area "Northeastern Atlantic, the Mediterranean and connected seas" (NEAMTHM18; http://ai2lab.org/tsumapsneam/interactive-hazard-curve-tool/, last accessed on March 2022) and map showing the distance between the sites where hazard estimates are provided (50 m isobaths) and the areas of interest

distance ranges from the areas of interest (namely at Adriatic-wide, regional and local scales). Selected basin-wide sources in the Mediterranean Sea are considered as well to assess the possible relevance to the AOI of tsunamis occurring outside the Adriatic Sea.

Tsunami modelling is performed by the NAMI DANCE software (Dogan et al. 2021a; Yalciner and Zaytsev 2017; Yalciner et al. 2017; Lynett et al. 2017; Velioglu et al. 2016), which allows accounting for seismic source properties, variable bathymetry and nonlinear effects in waves generation, propagation and inundation. The software has been successfully tested for recent tsunamis in the Mediterranean area and other regions (Celikbas et al. 2023; Dogan et al. 2021a, b, c; Dogan et al. 2023; Velioglu et al. 2016; Aytore et al. 2016). Three nested grids of bathymetry and topography are used in the computations, i.e. a coarse grid of about 400 m (Adriatic and Mediterranean scale) extracted from GEBCO 2020 data (https://download.gebco.net/), a medium grid of about 111 m (North Adriatic) produced from EMODnet data

and a fine grid of 20 m (area of interest) obtained from the work of Trobec et al. (2018). Accordingly, a set of maps of computed tsunami maximum amplitude are developed for sources located at different distances from the Northeastern Adriatic region, considering, in particular, the distance ranges adopted in the decision matrix (Fig. 1), and therefore relevant towards emergency management and planning mitigation actions at the selected sites (namely, Lignano, Grado, Monfalcone and Trieste).

This work consists of two main parts: in the first, we evaluate the hazard from the potential tsunamigenic sources located within the Adriatic Sea, which are categorized in this study into Adriatic-wide, regional and local sources, based upon their distance from the site of interest and given the tsunami decision matrix currently in force (Fig. 1). We provide maps of maximum tsunami wave amplitude for the whole grid till the shoreline of the area of interest, and nearshore wave amplitude at point of interests (POIs) (shown in supplementary material) for local, regional and Adriatic scales.
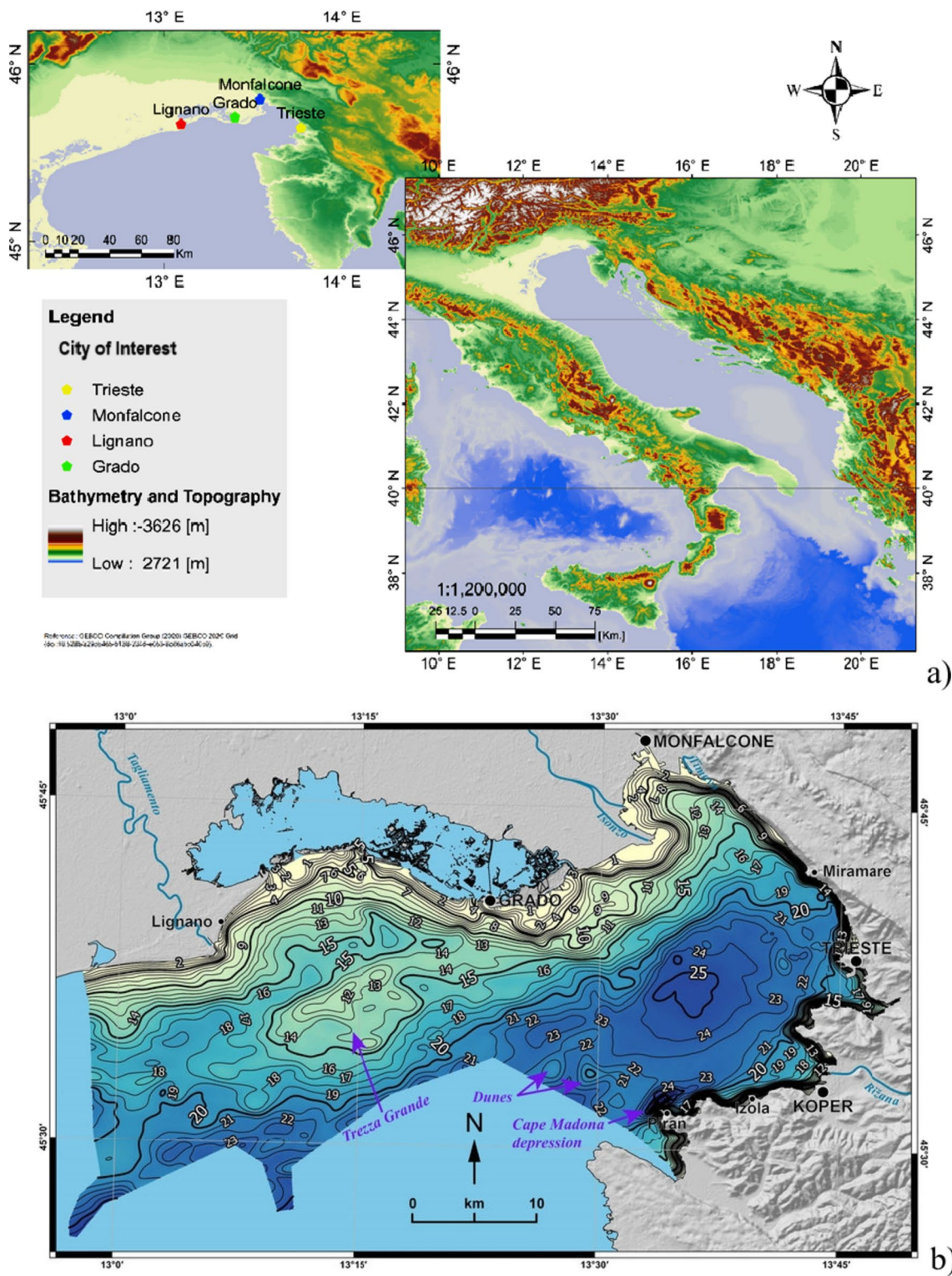
Fig. 3 Bathymetry and topography of the study area and the area of interest. The large domain, with coarse bathymetry, is taken from GEBCO-2020. The smaller domain is taken from EMODnet (**a**) and Trobec et al. (2018) (**b**)

Also, we provide the same maps for an aggregated scenario extracted from all possible scenarios within the Adriatic Sea at whatever distance. In the second part, we compute the

tsunami scenarios for possible very distant sources located outside the Adriatic Sea, hereinafter called basin-wide, from five main tsunamigenic earthquake zones (West Greece,

Table 1 Parameters of offshore tsunamigenic sources in the Adriatic Sea and the representative tsunami scenarios

Class	DISS-ID	Name	Updated DISS-3.3 M_{max}	DISS-3.2 M_{max}	Difference in M_{max}	Depth [km] Min	Depth [km] Max	Strike [deg] Min	Strike [deg] Max
Adriatic-wide tsunamigenic earthquake sources	ALCS002	Lushnje	7.5	7.2	0.3	2.0	15.0	310	340
	ALCS020	Seman Coastal	7.2	6.5	0.7	1.0	9.0	330	350
	HRCS001	Mljet	7.3	7.2	0.1	2.0	15.0	280	330
	HRCS002	Hvar	7.3	6.5	0.8	2.0	15.0	260	310
	HRCS004	Eastern Adriatic offshore—South	6.9	6.0	0.9	2.0	12.0	270	330
	HRCS007	Vis-Korcula	7.3	5.8	1.5	2.0	15.0	270	290
	HRCS010	Palagruza	6.9	6.0	0.9	2.0	12.0	275	350
	ITCS059	S. Benedetto-Giulianova offshore	7.5	5.8	1.7	1.0	20.0	80	100
	ITCS074	Shallow Gondola Fault Zone	6.9	6.5	0.4	0	14.0	270	280
	MECS001	Montenegro offshore	8.0	7.2	0.8	2.0	15.0	290	310
	MECS007	Budva Offshore	7.1	6.5	0.6	1.0	10.0	270	350
Regional tsunamigenic earthquake sources	ITCS031	Conero offshore	6.6	6.0	0.6	1.5	7.0	125	155
	HRCS021	Eastern Adriatic offshore—North	6.9	6.0	0.9	2.0	12.0	270	330
	HRCS014	Jana-1	6.9	6.0	0.9	2.0	12.0	275	350
	HRCS020	Eastern Adriatic offshore—Central	6.9	6.0	0.9	2.0	12.0	270	330
	HRCS008	Dugi Otok	7.5	6.0	1.5	2.0	18.0	280	330
	HRCS018	Vis-West	6.9	5.8	1.1	2.0	15.0	280	330
	HRCS025	Krk	7.2	6.0	1.2	1.0	15.0	320	340
	ITCS004	Castelluccio dei Sauri-Trani	7.3	6.3	1.0	11.0	22.5	260	280
	ITCS039	Riminese onshore	7.0	5.9	1.1	2.0	10.0	120	140
	ITCS070	Deep Gondola Fault Zone	7.2	6.5	0.7	0	14.0	270	280
	ITCS106	Pesaro mare-Cornelia	6.5	5.5	1.0	2.0	7.0	120	160
	ITCS108	Clara	6.5	5.5	1.0	2.0	8.0	95	120
	ITCS134	Roseto degli Abruzzi	6.9	5.5	1.4	4.5	15.0	65	75
	ITCS154	Edmond	6.8	5.5	1.3	2.6	9.0	109	190
	ITCS155	Daniel	6.5	5.5	1.0	3.2	10.0	299	354
	ITCS158	Valeria	6.6	5.5	1.1	4.3	10.0	294	353
Local tsunamigenic earthquake sources	ITCS100	Northern Trieste Gulf	6.9	6.5	0.4	1.0	10.0	320	350
	ITCS101	Southern Trieste Gulf	6.5	6.5	0	1.5	8.0	290	330

Class	Dip [deg] Min	Dip [deg] Max	Rake [deg] Min	Rake [deg] Max	Epicentre of the representative scenarios Lat [deg]	Lon [deg]	Fault dimension (km) Length	Width	Amplitude at the source area (m) Min	Max
Adriatic-wide tsunamigenic earthquake sources	25	40.0	80	100	40.87	19.54	85.1	11.0	−0.61	3.26
	20	40	80	100	40.64	19.41	57.0	8.5	−0.55	2.96
	30	45	70	110	42.58	17.87	65.1	9.2	−0.42	3.13
	40	70	20	70	43.06	16.88	65.1	9.2	−0.18	0.86
	35	60	70	100	42.62	16.41	38.2	6.5	−0.19	1.91
	40	70	20	70	42.86	16.71	65.1	9.2	−0.48	2.29
	35	50	70	100	42.23	16.44	38.2	6.5	−0.46	1.79
	65	90	170	230	42.15	14.70	85.1	11.0	−0.56	0.22

Table 1 (continued)

| Class	Dip [deg]		Rake [deg]		Epicentre of the representative scenarios		Fault dimension (km)		Amplitude at the source area (m)	
	Min	Max	Min	Max	Lat [deg]	Lon [deg]	Length	Width	Min	Max
	80	90	220	230	41.63	17.02	38.2	6.5	− 0.48	0.37
	15	40	80	100	41.69	19.42	166.0	17.0	− 1.13	6.02
	25	35	80	110	41.87	19.27	50.0	7.7	− 0.14	0.14
Regional tsunamigenic earthquake sources	25	40	80	100	43.45	13.72	25.5	5.0	− 0.28	1.54
	35	60	70	100	44.14	13.88	38.2	6.5	− 0.19	1.92
	35	50	70	100	42.78	15.15	38.2	6.5	− 0.06	0.77
	35	60	70	100	43.12	15.13	38.2	6.5	− 0.19	1.92
	30	45	90	120	43.59	15.56	85.1	11.0	− 0.47	3.54
	50	70	90	120	43.08	16.09	38.2	6.5	− 0.26	1.85
	40	50	110	130	44.80	14.83	57.0	8.4	− 1.00	0.19
	70	90	170	190	41.27	16.51	65.1	9.2	− 0.14	0.14
	25	35	80	100	44.20	12.45	43.6	7.0	− 0.21	2.02
	80	90	220	230	41.63	16.79	57.0	8.4	− 0.48	0.37
	25	40	80	100	43.95	13.21	22.3	4.5	− 0.16	1.28
	30	40	80	100	43.74	14.04	22.3	4.5	− 0.16	1.29
	50	70	120	150	42.62	14.07	38.2	6.5	− 0.10	0.45
	20	60	80	100	42.79	14.63	33.4	6.0	− 0.10	0.46
	32	75	80	100	43.31	14.29	22.3	4.5	− 0.10	0.74
	24	48	80	100	43.46	14.23	25.5	5.0	− 0.10	0.76
Local tsunamigenic earthquake sources	50	60	130	160	45.61	13.85	38.2	6.5	− 0.14	1.53
	30	45	100	120	45.54	13.86	22.3	4.5	− 0.10	0.75

Calabrian, West Hellenic, East Hellenic and Cyprian Arcs). The tsunami scenarios of the maximum expected earthquake (based on historical seismicity or geological surveys) within each source were computed, and an aggregated scenario was extracted. Moreover, maps of maximum wave amplitude for aggregated scenarios at basin and area of interest scales are given for each tsunamigenic earthquake zone.

2 Tsunami modelling

Tsunami modelling usually relies on a specific model, namely a mathematical formulation that describes the physical characteristics of the tsunami, to compute the generation and propagation of tsunami waves and their coastal impact. The tsunami modelling process comprises three phases: (a) source modelling, in which the initial conditions of the tsunami source are computed (i.e. initial sea surface displacements and velocity fields); (b) propagation modelling, to be used to describe the propagation of tsunamis in the open sea;

(c) inundation modelling, in which coastal modification of tsunami waves and run-up, in shallow regions and on land, is treated. The last phase is possibly the most important in tsunami modelling, as suitable tools and data are essential for accurate quantification.

Numerical models (i.e. computer-derived simulation packages) generally use a grid system for the area of interest that includes information about the source, bathymetry, topography and surface roughness or land use. Therefore, a numerical model can incorporate complicated geographic variations in bathymetry, topography and land uses, and can simulate different stages of tsunamis, including wave amplitude, current speed and inundation depth variations. The recent tsunami models simulate tsunami generation, propagation and inundation stages, overcoming the challenge of abrupt changes in conditions at the shore, which is the most dynamic and complex stage of tsunami modelling. Among the available models, COMCOT (Cornell University, USA; GNS Science, New Zealand), TUNAMI-N1/N2 (Tohoku University, Japan) and MOST (National Center for
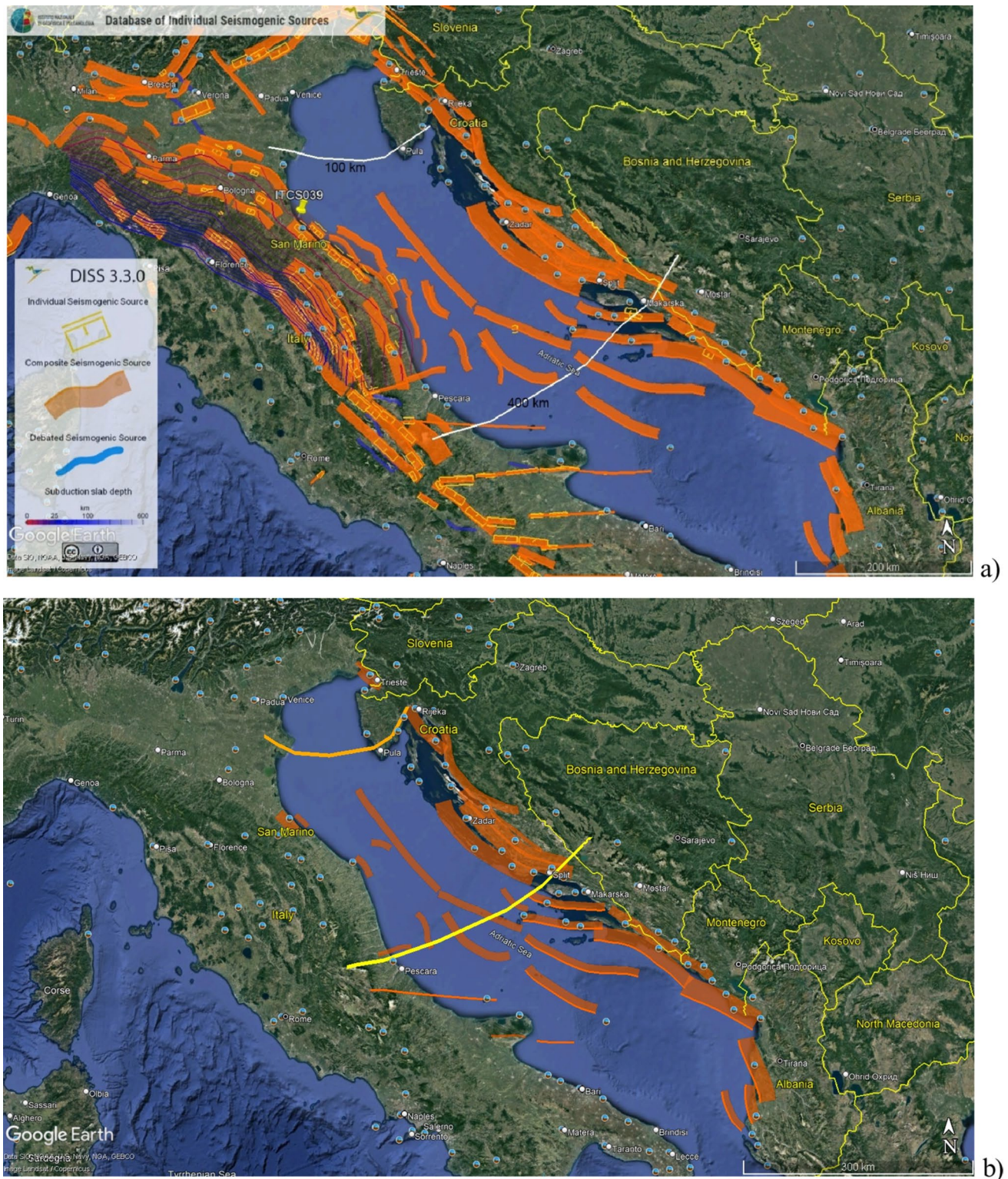
Fig. 4 Seismogenic sources from DISS-3.3 (DISS Working Group 2021), including **a** all sources and **b** the selected tsunamigenic sources in the Adriatic Sea located at different locations in the area of interest. Orange and yellow lines indicate the 100 km and 400 km limits, respectively

Fig. 5 Tsunamigenic earthquake sources at Adriatic-wide scale (distance from the AOI is > 400 km). The yellow line defines the sources at more than 400 km, while red rectangles are the tsunamigenic sources

Tsunami Research, USA) have demonstrated their capacity in investigating the three stages of tsunami evolution. In this study, we perform the tsunami numerical modelling by the code NAMI DANCE (Middle East Technical University-METU, Turkey), which represents an extension and update of the model TUNAMI-N1/N2 and is based on the solution of the nonlinear form of the long wave equations with respect to related initial and boundary conditions. In general, the most common and proper solution upon which the codes are developed is the numerical solution in nonlinear shallow water approximation (Imamura 1988), which neglects the vertical variation of velocity over water depth because tsunami wavelengths are usually much larger than ocean depths.

The tsunami modelling computation carried out in this study is based on a nonlinear shallow water equation. The role of roughness is considered by attributing a friction coefficient of 0.015, taken from Chow (1960). As far as the source model is concerned, the NAMI DANCE code follows the Okada (1985) relations, which provide the numerical result of the elastic seabed displacement of the co-seismic deformation, to compute the initial condition for the shallow

water wave equation (Dogan et al. 2021a; Yalciner and Zaytsev 2017; Yalciner et al. 2017; Lynett et al. 2017; Velioglu et al. 2016). For modelling purposes, a finite rectangular source model is defined by the following parameters: epicentral coordinates, strike, dip, rake, depth, amount of slip, length L and width W. The Okada (1985) model for fault slip is linear; hence, if necessary, it is possible to model a complex rupture as a group of source segments, each with a different amount of slip. However, Okada's model neglects the spatiotemporal variations in slip, which are essential for assessing tsunami impacts in regions close to the earthquake source. Geist and Dmowska (1999) showed that local tsunami run-up can vary over a factor of 3, depending on the slip distribution. Therefore, spatiotemporal variation in fault rupture is considered when treating the local tsunamigenic sources in the Gulf of Trieste by segmenting the source into sub-sources with variable rupture slip and velocity.

3 Bathymetry and topographic dataset

Three nested grids of bathymetry and topography have been used in the computations, namely: a coarse grid of about 400 m spatial resolution at the Adriatic and Mediterranean scale, a medium grid of about 111 m resolution for North

(a)

(b)
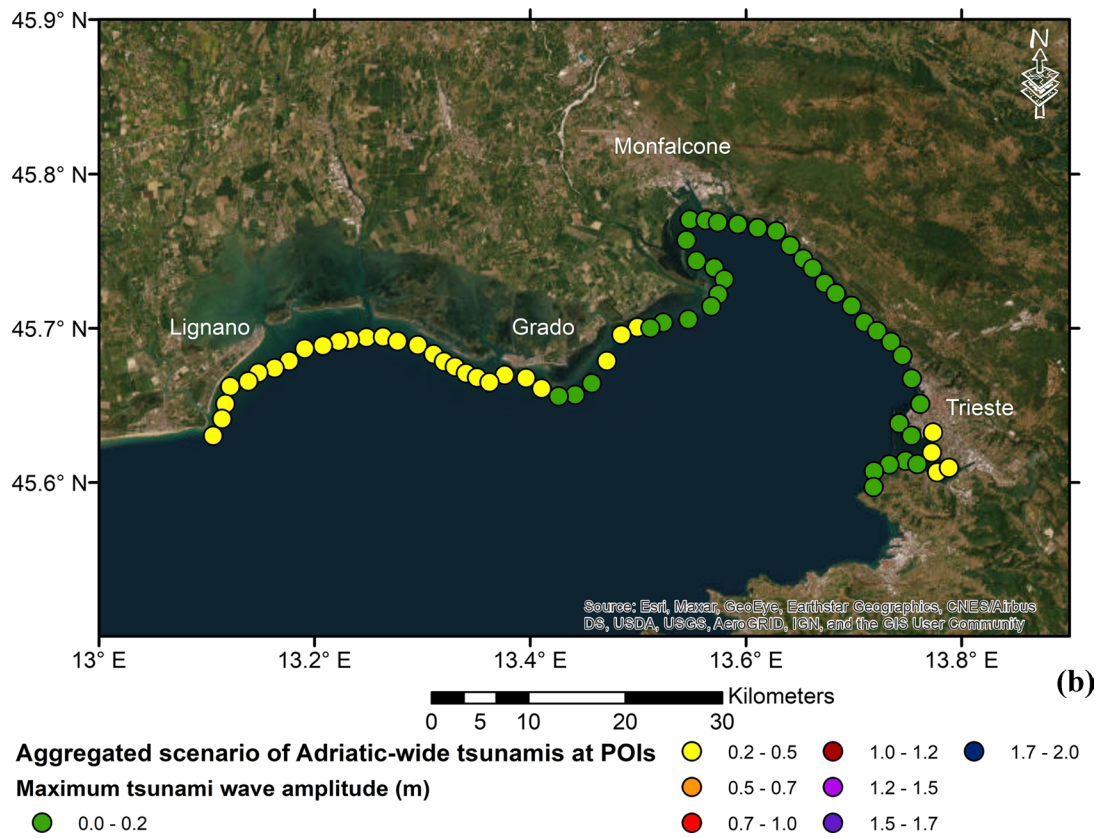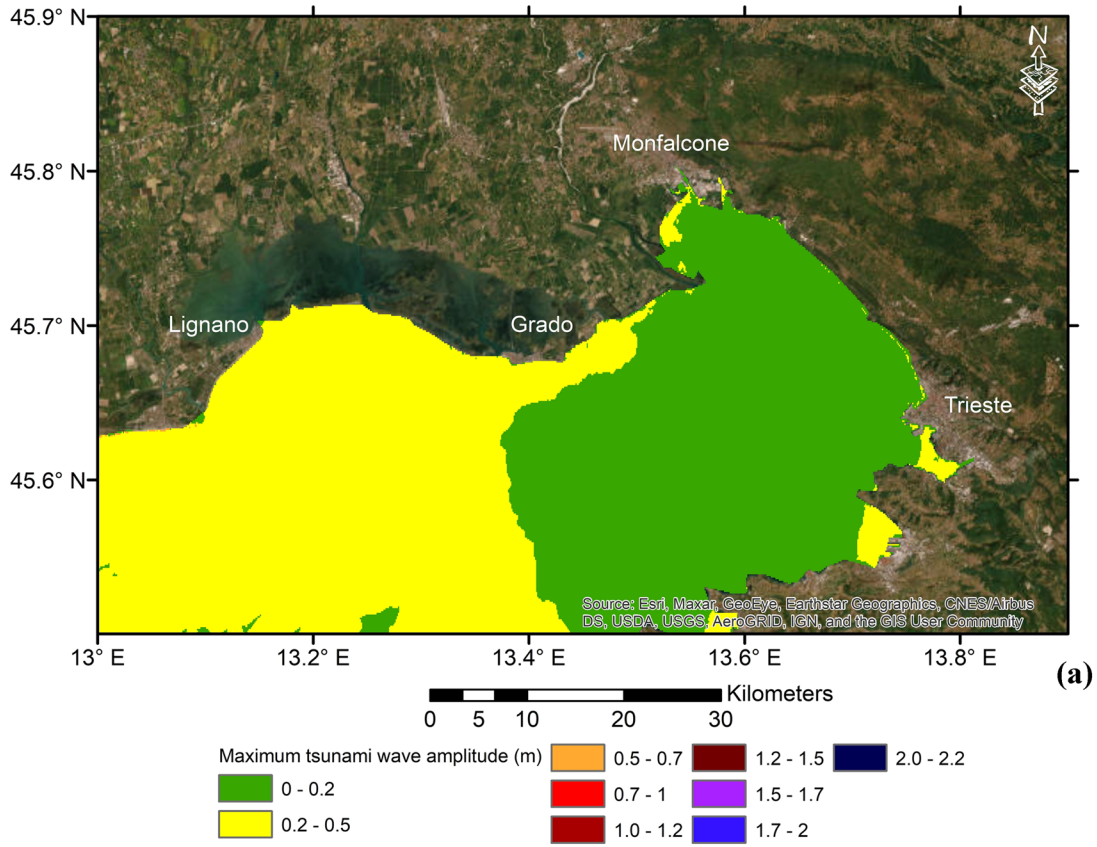
◄**Fig. 6 a** Map of the maximum tsunami wave amplitude computed for the Adriatic-wide sources (listed in Table 1) located at distances greater than 400 km from the area of interest (AOI). **b** The maximum tsunami wave amplitude computed for the Adriatic-wide sources (listed in Table 1) at the selected POIs

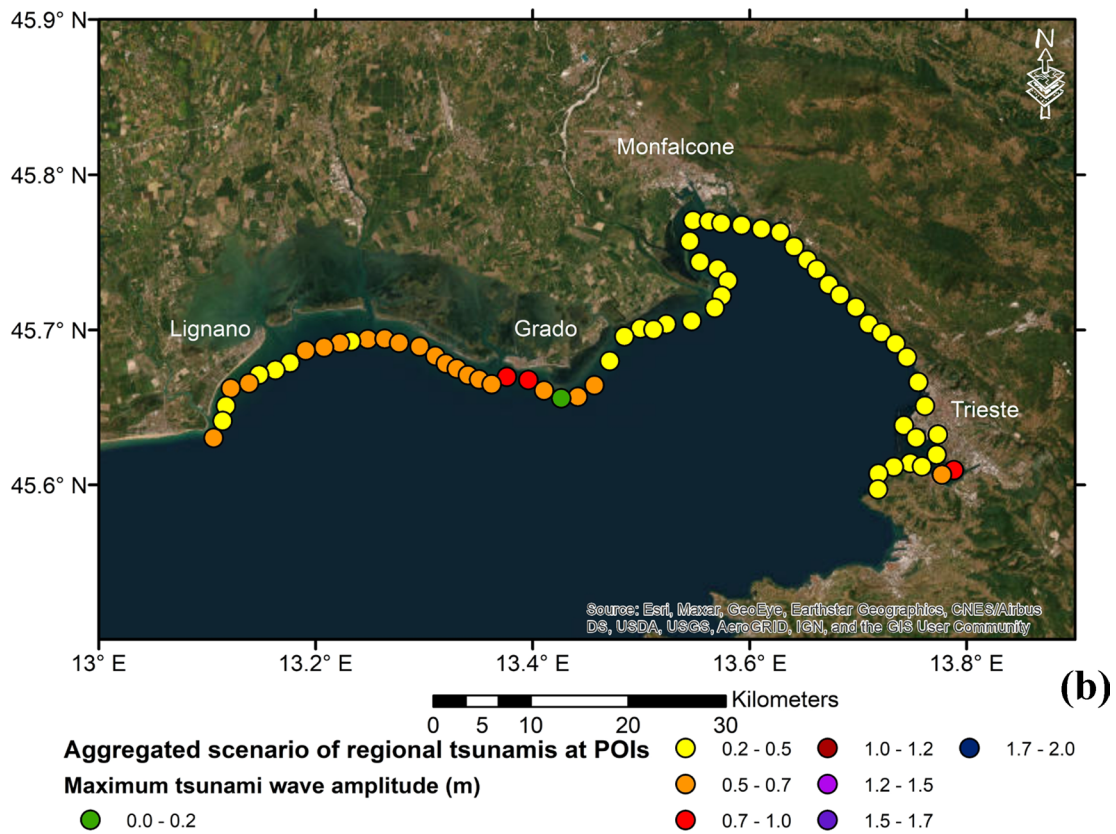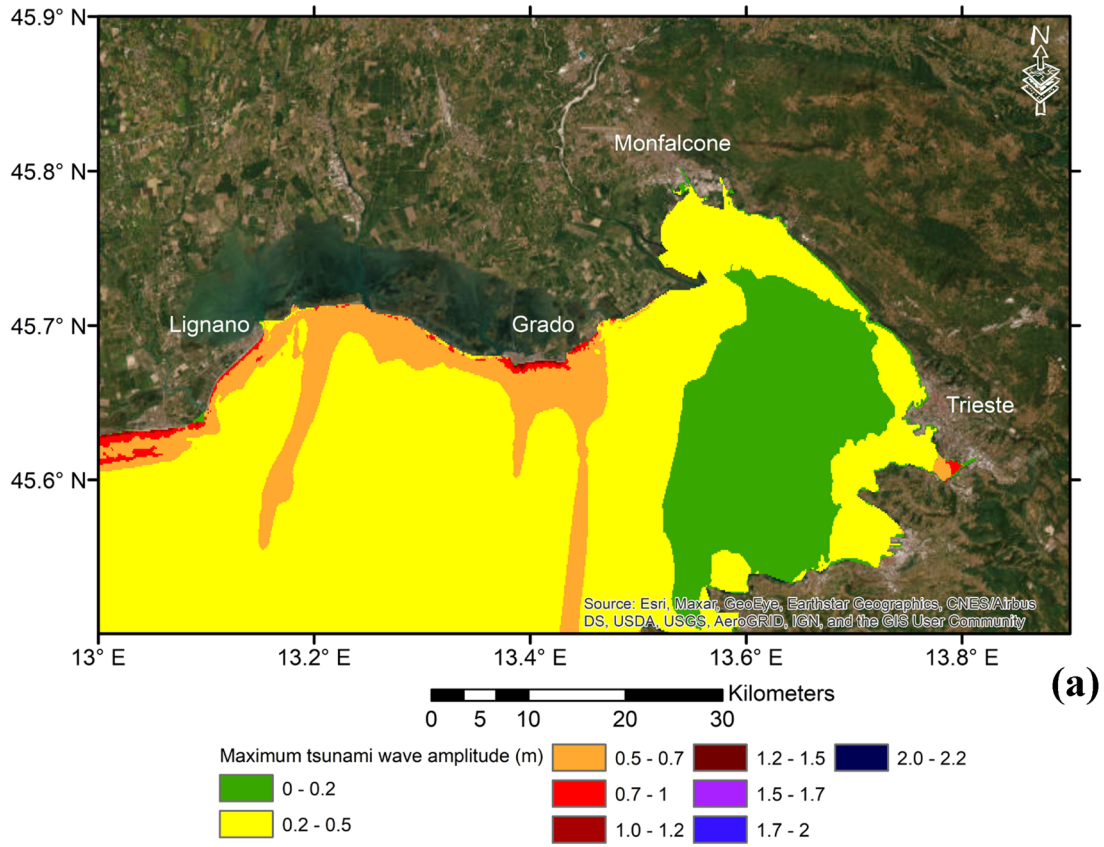Adriatic and a fine grid of 20 m resolution for the area of interest.

The bathymetry and topography data were extracted, inspected, processed and then converted into the format required by the tsunami modelling code (NAMI DANCE). The coarse-domain bathymetry and topography grids of about 400 m spatial resolution (parent) for the Eastern Mediterranean and Adriatic seas were extracted from GEBCO-2020 (GEBCO Compilation Group 2020). Also, medium-domain resolution grids of about 111 m were obtained and processed from the EMODnet portal (https://portal.emodnet-bathymetry.eu/). Finally, a fine bathymetry and topography grid of about 10 m resolution for the Northeastern Adriatic, where the municipalities of interest (AOI) are located, was provided by Trobec et al. (2018), who used various geophysical datasets to develop a detailed bathymetry model of the Gulf of Trieste (Fig. 3). Topographic or land data were extracted from Copernicus DEM- Global and European Digital Elevation Model (COP-DEM) of 10 m cell size. It is worth noting that in this study, the grid

of 10 m resolution was de-sampled into a 20 m resolution grid due to current computational limits; the lower resolution grid, however, might not allow to capture some crucial features of the wetlands within the area of interest (e.g. Marano Lagoon, between Lignano and Grado). However, while the 20 m resolution grid might not be sufficient for a detailed inundation modelling, it could still be adequate for estimating the maximum tsunami amplitude and the estimated time of arrivals (ETA) for the area of interest, namely to meet the requirements of the civil protection of the FVG region. A careful examination of the considered bathymetry dataset revealed some artefacts (e.g. closed openings) that could affect the propagation of tsunami waves behind the shoreline. For instance, the closed openings to lagoons in the de-sampled bathymetry dataset may prevent tsunamis from progressively propagating within the wetlands. Therefore, the bathymetry data for these areas require careful analysis in the preprocessing stage and should be properly modified to accurately reflect the real situation, to allow computing the tsunami inundation. A focused and detailed mapping is foreseen in these areas, particularly the Marano Lagoon, and it must be developed for effective exposure, vulnerability and risk analysis at some sites of interest.

The maps of topography and bathymetry of the study region (Fig. 3) indicate that the deeper part is located in the southern part of the Adriatic Sea, while the northern
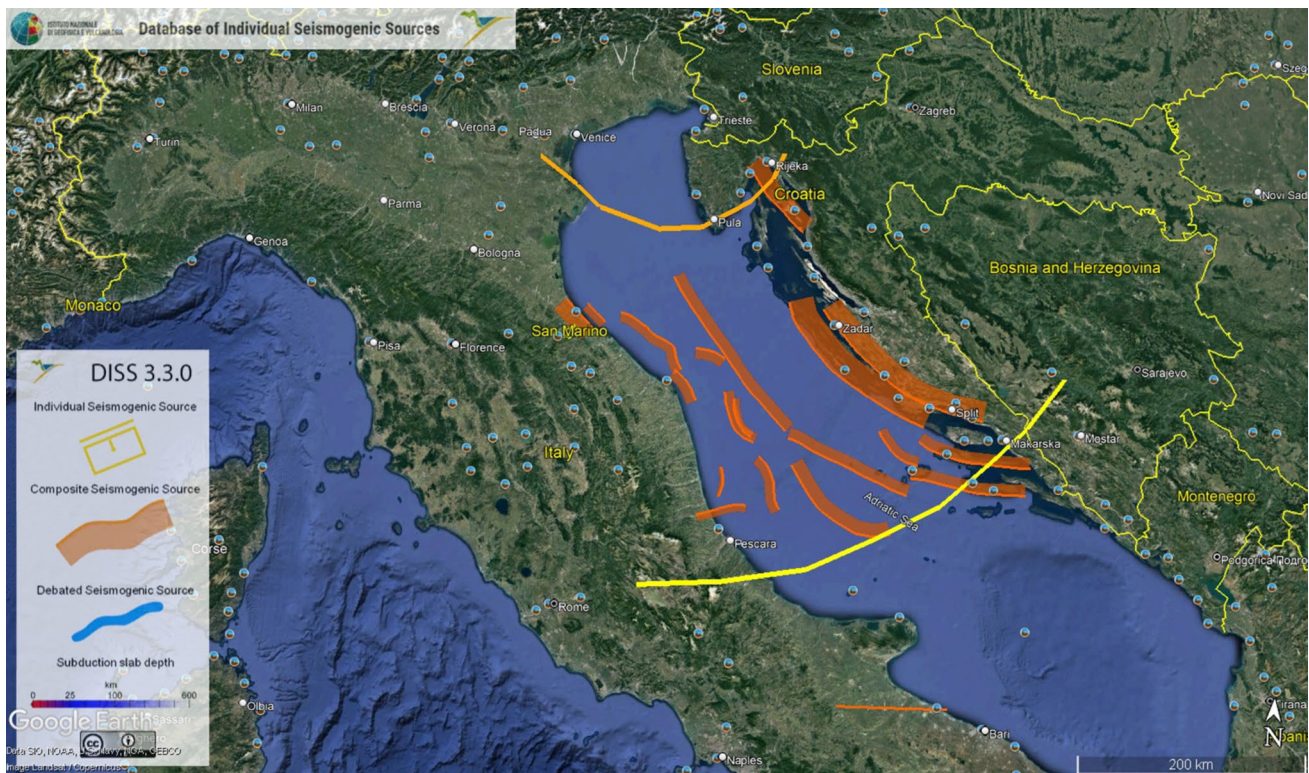
Fig. 7 Tsunamigenic earthquake sources at regional scale (distance from the AOI is > 100 and ≤ 400 km). The orange line defines the 100 km epicentral distance, while the yellow line defines the 400 km epicentral distance; red rectangles represent tsunamigenic sources

(a)

Maximum tsunami wave amplitude (m)
- 0 - 0.2
- 0.2 - 0.5
- 0.5 - 0.7
- 0.7 - 1
- 1.0 - 1.2
- 1.2 - 1.5
- 1.5 - 1.7
- 1.7 - 2
- 2.0 - 2.2

(b)

Aggregated scenario of regional tsunamis at POIs
Maximum tsunami wave amplitude (m)
- 0.0 - 0.2
- 0.2 - 0.5
- 0.5 - 0.7
- 0.7 - 1.0
- 1.0 - 1.2
- 1.2 - 1.5
- 1.5 - 1.7
- 1.7 - 2.0

◄**Fig. 8** **a** Map of the maximum tsunami wave amplitude computed for the regional tsunamigenic sources (listed in Table 1). **b** The maximum tsunami wave amplitude computed for the regional tsunamigenic sources at POIs (listed in Table S1)

part is very shallow, with a water depth of less than 50 m. Noteworthy, due to the shallow bathymetry, the tsunami waves propagate with very low velocity in the Northern Adriatic Sea. This is a significant advantage, especially for distant tsunamigenic sources, as more time is available to alert people and to take emergency actions.

4 Computation of tsunamigenic earthquake scenarios in the Adriatic Sea

One of the goals of this study is to provide physically consistent tsunami hazard estimates based on the modelling of tsunami wave propagation from an extensive set of possible sources to be considered in case an alert is issued by the CAT-INGV tsunami warning system. Hence, we first defined the possible tsunamigenic earthquake sources located in the Adriatic Sea based on the recently updated DISS database (DISS-3.3 http://diss.rm.ingv.it/diss/) and following the tsunami decision matrix developed by CAT-INGV (Fig. 1). According to the decision matrix, a seismogenic source is considered tsunamigenic, of potential weak local tsunami (distance ≤ 100 km), if it is capable of producing shallow offshore earthquakes of magnitude $M \geq 6$. Therefore, we compiled a database (Table 1 and Fig. 4) of local tsunamigenic earthquake sources of $M_{max} \geq 6$ relative to our area of interest from the DISS-3.3 database (Fig. 4) and $M_{max} \geq 6.5$ for regional (100 km < distance ≤ 400) and basin-wide (distance > 400 km) tsunamis, to evaluate the potential tsunami hazard at different distances and to serve as pre-computed scenarios in case a future tsunami alert is activated. This way, the best-matched pre-computed scenario (in location and magnitude) results can be identified, extracted and used for a quick response in case of tsunamigenic earthquake occurrence. Notably, the maximum magnitude of most seismogenic sources within the DISS-3.3 was upgraded (i.e. generally increased) in a 0–1.7 magnitude unit (Table 1) relative to the previous DISS-3.2.1 version. Therefore, according to the updated DISS-3.3, a more substantial number of seismogenic sources prove capable of generating tsunamis, compared to the former DISS version used by Peresan and Hassan (2022), because the magnitude increased for several sources.

Based on parametric studies, for each scenario, the parameters composing the worst-case scenario in terms of strike, dip, rake and focal depth were extracted from the given range in the DISS database and then adopted (geo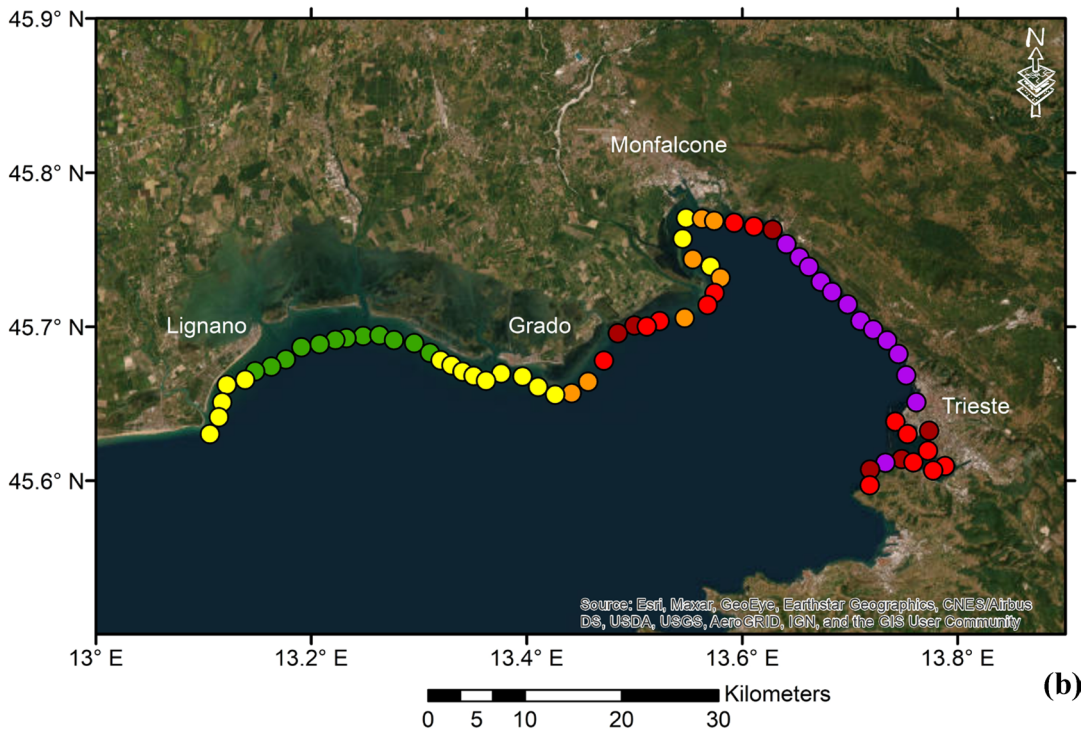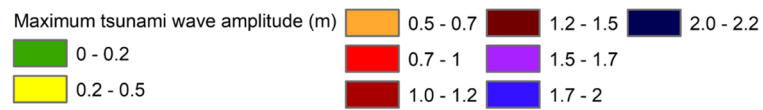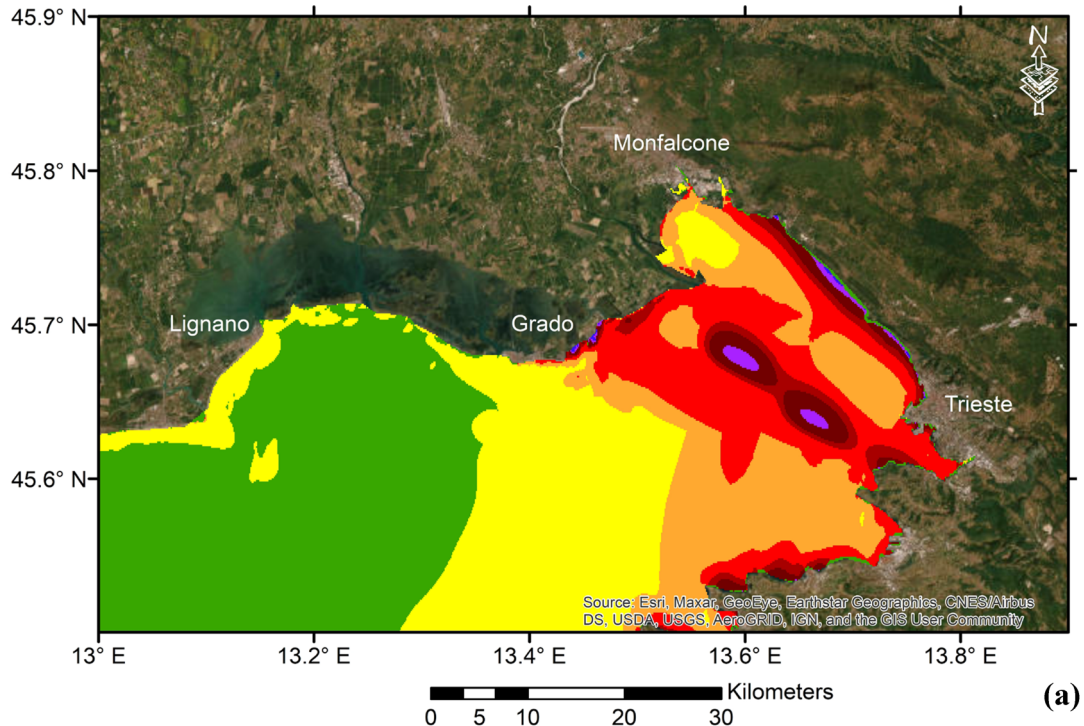metry and kinematic parameters). In addition, the fault length, width and slip were estimated from the source scaling relationship of Wells and Coppersmith (1994) and recent studies, as reported in Table 1. More than a hundred individual scenarios were simulated during this work; maps of maximum tsunami wave amplitude at each grid and POIs nearshore (listed in supplementary material, Table S1) were then developed for local, regional and Adriatic-wide tsunamis (the computed scenarios and the related maps are available in digital format).

4.1 Adriatic-wide tsunamigenic earthquake sources

Following the described procedure, 13 seismogenic sources with $M_{max} \geq 6.5$, located at distances greater than 400 km from our area of interest, were selected to compute Adriatic-wide tsunami scenarios. These sources are: ALCS002, ALCS004, ALCS018, ALCS020, HRCS001, HRCS002, HRCS004, HRCS007, HRCS010, ITCS059, ITCS074, MECS001 and MECS007 and their M_{max} range between 6.9 and 8; of note, most of the powerful tsunamigenic sources are located along the Eastern coast of the Adriatic Sea. The scenarios for the selected sources (Fig. 5) are simulated individually, and then an aggregated scenario is developed (Fig. 6). The computed maximum tsunami wave amplitude at each grid point till shoreline for our AOI is up to 0.5 m, as shown in Fig. 6a. The maximum wave amplitude is provided at given POIs as well (Fig. 6b) and indicates maximum wave amplitude of 0.5, 0.4, 0.2 and 0.2, for Lignano, Grado, Monfalcone and Trieste, respectively. The estimated arrival time (ETA) varies from source to source, with a minimum arrival time of 272–280 min for these cities.

4.2 Regional tsunamigenic earthquake sources

From now on, following the decision matrix, the seismogenic sources with $M_{max} \geq 6.5$ located at a distance between 100 and 400 km from our area of interest were considered. Accordingly, more than 15 seismogenic sources from DISS were defined as potentially tsunamigenic (Fig. 7). They were simulated individually, and then an aggregated scenario was developed (Fig. 8). The computed maximum tsunami wave amplitude for our AOI was up to 1.0 m at some sites (Fig. 8a). The regional tsunami sources were found to impose a higher hazard to the AOI, compared to the Adriatic-wide tsunami sources. The maximum wave amplitude along the shoreline is provided at given POIs as well (Fig. 8b). The simulated scenarios indicate a maximum wave amplitude of 0.9, 1.0, 0.4 and 0.4 m for Lignano, Grado, Monfalcone and Trieste, respectively. Moreover, the minimum arrival time ETA ranged between 107 and 115 min for these cities.

(a)

Maximum tsunami wave amplitude (m)
- 0 - 0.2
- 0.2 - 0.5
- 0.5 - 0.7
- 0.7 - 1
- 1.0 - 1.2
- 1.2 - 1.5
- 1.5 - 1.7
- 1.7 - 2
- 2.0 - 2.2

(b)

Aggregated scenario of local tsunamis at POIs
Maximum tsunami wave amplitude (m)
- 0.0 - 0.2
- 0.2 - 0.5
- 0.5 - 0.7
- 0.7 - 1.0
- 1.0 - 1.2
- 1.2 - 1.5
- 1.5 - 1.7
- 1.7 - 2.0

◀**Fig. 9 a** The maximum tsunami wave amplitudes for local sources (i.e. ITCS100 and ITCS101) located at distances less than 100 km from the area of interest. **b** The maximum tsunami wave amplitude computed for the local tsunamigenic sources (i.e. ITCS100 and ITCS101) at POIs

4.3 Local tsunamigenic earthquake sources

Two local offshore seismogenic sources were defined in the Northeast Adriatic region according to the DISS-3.3 database (Table 1 and Fig. 4; for further details, see DISS Working Group 2021). These earthquake sources were named the Southern and the Northern Trieste Gulf, as indicated in Table 1, and assigned magnitudes M_{max} 6.5 and 6.9, respectively. These two sources are considered tsunamigenic because of their assigned location, magnitude and focal mechanism, and they might impact the AOI with strong ground motion and tsunami waves if they occur.

In the current study, the local seismogenic sources were considered in developing the tsunami hazard estimation. The spatiotemporal variation in fault rupture was considered here by segmenting the sources into sub-sources with rupture slip and velocity that varied along the scenario fault. The off-shore source was segmented into 7-km-long sub-sources, with slip and rupture velocities increasing in a unilateral NW direction. This source shall be studied in detail in future developments, considering different rupture styles (i.e. uni-lateral, bilateral) and directivity angles, representing different potential scenarios in future ruptures. The computed maximum tsunami wave amplitude at POIs was up to 2.0 m (Fig. 9). Specifically, a maximum wave amplitude of 2.0 m is estimated for Trieste and Grado, while Monfalcone and Lignano have 1.0 and 0.4 m, respectively.

5 Basin-wide tsunami sources (out of the Adriatic Sea)

Based on the CAT-INGV's tsunami matrix (Fig. 1), an off-shore or inland, shallow earthquake (i.e. depth < 100 km) of magnitude larger than 7.5 has the potential to generate a destructive tsunami affecting the whole Mediterranean basin at any distance. Accordingly, tsunami scenarios were modelled for potential seismogenic zones of magnitude higher than 7.5 outside the Adriatic Sea, namely: West Greece, West Hellenic, Calabrian Arc, East Hellenic and Cyprian Arc zones. GEBCO 2020 bathymetry and topography data of about 400 m resolution were used for the entire basin (Fig. 10). The maximum wave amplitude was computed for the area of interest in the Northern Adriatic (Fig. 11), considering the seismic source parameters shown in Table 2. Fault slip parameters for tsunami scenario computation were collected from DISS-3.3 and individual studies (England

et al. 2015; Hassan et al. 2023). For each seismogenic zone separately, several scenarios accounting for source uncertainties were computed, and tsunami wave amplitude maps developed as aggregated scenarios of maximum estimated values.

The computed scenarios can be used, jointly with real-time seismic and sea-level tide measurements, to provide a quantitative basis for the decision-making process by emergency managers and first responders in the FVG region in case of future large tsunamigenic earthquake occurrence in one of the considered zones.

5.1 West Greece zone

The western coast of Greece lies along the Ionian Sea, which is relatively less prone to tsunamis compared to other areas of the Mediterranean Sea, such as the eastern coast of the Mediterranean. However, it is important to note that tsunamis can still occur in the Ionian Sea due to various factors such as earthquakes, underwater landslides and volcanic eruptions. The most significant event to hit the western coast of Greece in recent history was associated with the 1953 Ionian earthquake, which triggered a tsunami that caused substantial damage and loss of life in the region (Mavroulis and Lekkas 2021).

Five individual tsunami scenarios (Table 2) were modelled and an aggregated scenario of maximum wave amplitude was extracted (Fig. 11). The resulting maximum wave amplitude at the AOI ranges between 0.10 and 0.44 m as shown in the bottom panel of Fig. 11.

5.2 Calabrian Arc zone

The Calabrian Arc is considered a high-risk area for tsunamis due to seismic activity and underwater landslides. The area has experienced several significant tsunamis in the past, including the 1908 Messina earthquake and tsunami (e.g. Schambach et al. 2020), which caused widespread devastation and loss of life in the region.

Eight individual tsunami scenarios (Table 2) were modelled within the Calabrian Arc zone (Fig. 10), and an aggregated scenario was then produced (Fig. 12). The computed maximum nearshore wave amplitude, computed at the AOI, is about 0.2 m (Fig. 12, bottom panel).

5.3 West Hellenic Arc zone

The West Hellenic Arc is a seismically active area located in the Eastern Mediterranean Sea (Fig. 10). This arc is part of the larger Hellenic Arc, which is a curving chain of tectonic plate boundaries that extends from the western coast of Greece to the southern coast of Turkey. The Hellenic Arc results from the subduction of the African Plate beneath
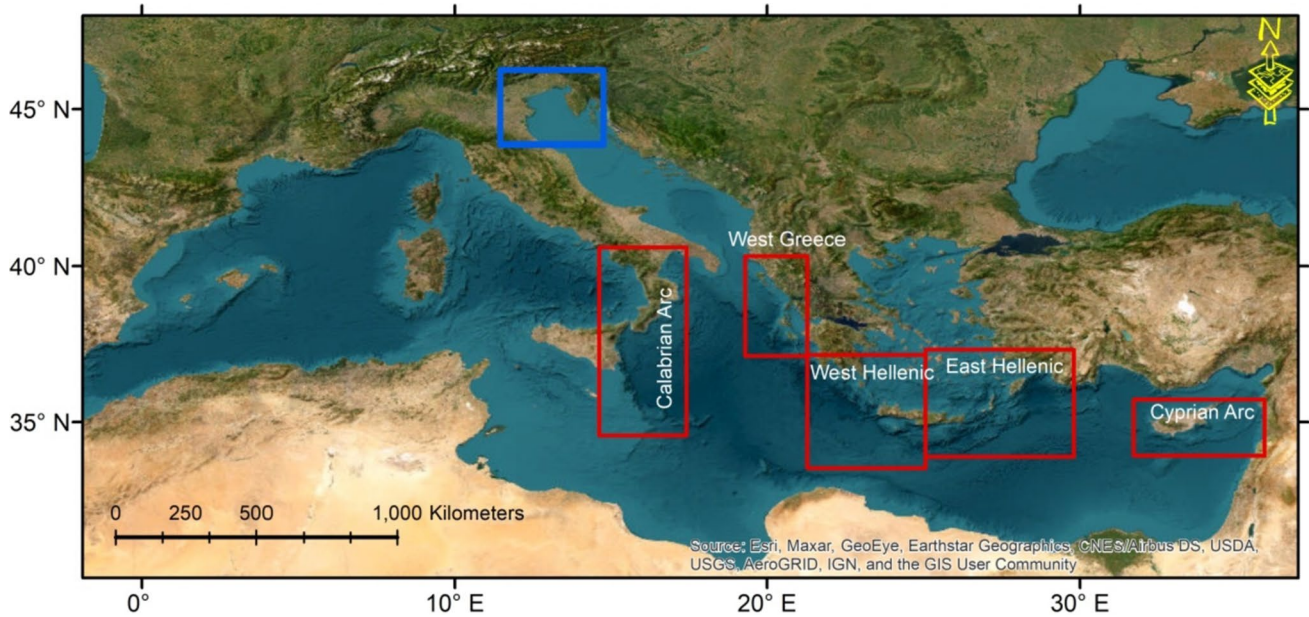
Fig. 10 Basin-wide tsunami sources (red rectangles) within which individual scenarios are modelled, and the maps of maximum wave amplitude are computed and presented for the AOI (blue rectangle)
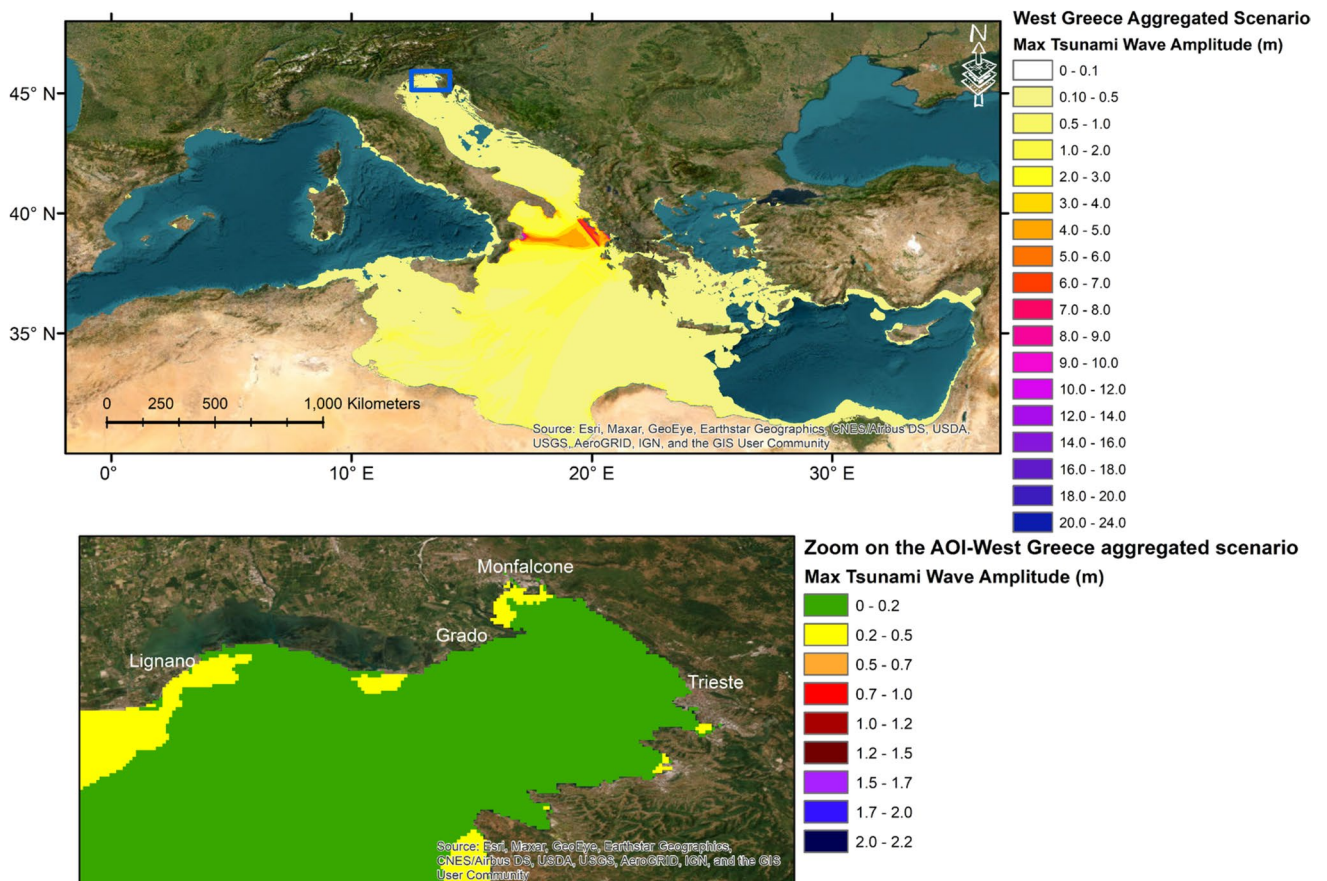
Fig. 11 Aggregated scenario from the individual scenarios (listed in Table 2) computed for the West Greece zone at basin-wide scale (top) and a zoom on the area of interest (bottom)

Table 2 Parameters of basin-wide tsunamigenic sources in the Mediterranean Sea adopted in the computation of maps of the maximum tsunami wave amplitude

Zone	ID	CSS-name	Mmax DISS-3.3	Depth [km] Min	Max	Strike[deg]		Dip[deg]	
West Greece Zone	ITCS096	Calabria Offshore S	7.9	4	12	190	270	10	20
	ITCS097	Calabria Offshore SW	7.9	4	12	180	280	10	20
	ITCS098	Calabria Offshore NE	7.4	4	9	180	260	10	20
	MTCS001	Malta N	7.5	3	15	120	140	50	75
	ITCS099	Calabria Offshore NW	7.9	3	12	180	250	10	40
Calabrian Arc Zone	ALCS001	Sazani	7.6	1	15	290	340	25	40
	GRCS606	Mediterranean North	7.8	5	16	300	360	15	35
	GRCS607	Zakinthos Offshore	7.8	5	17	305	360	15	40
	GRCS604	Kerkyra Offshore	8.0	3	20	280	350	20	40
	GRCS603	Kephallonia	7.4	4	25	10	50	50	70
	GRSD001	Southwestern Crete	8.5	5	54	300	314	20	35
West Hellenic Arc Zone	S1	West Hellenic	8.5		45		326		30
	S2	West Hellenic	8.5		45		326		35
	S3	West Hellenic	8.5		45		326		30
	S4	West Hellenic	8.5		45		326		30
East Hellenic Arc Zone	S5	East Hellenic	8.0		45		250		30
	S6	East Hellenic	8.0		45		250		30
	S7	East Hellenic	8.0		45		250		30
	S8	East Hellenic	8.0		40		250		35
Cyprian Arc Zone	S9	Cyprian Arc	8.0		5		280		20

Zone	Rake [deg]		Epicentre of the representative scenarios Lat [deg]	Lon [deg]	Fault dimension (km) Length	Width	Amplitude at the source area (m) Min	Max	Reference
West Greece Zone	80	100	37.20	17.14	145.2	15.5	−2.72	6.05	DISS-3.3
	80	100	37.28	17.01	145.2	15.5	−2.72	6.05	
	80	100	38.16	18.45	73.1	10.1	−1.07	2.31	
	190	240	35.44	14.82	85.1	11.0	−1.07	0.54	
	80	100	38.33	17.68	145.2	15.5	−1.37	8.03	
Calabrian Arc Zone	80	100	39.96	19.86	97.2	12.0	−0.65	3.50	
	80	100	36.99	20.38	127.0	14.2	−0.94	2.62	
	80	100	37.25	20.59	127.0	14.2	−0.75	2.71	
	80	100	38.58	20.31	166.0	17.0	−1.19	7.71	
	140	180	37.69	19.78	74.4	10.0	−0.93	2.89	
	90	100	37.02	20.58	323.0	26.3	−0.72	9.96	
West Hellenic Arc Zone		90	34.79	23.90	100.0	75.0	−0.92	5.44	England et al. (2015)
		90	34.51	24.01	170.0	75.0	−0.65	5.57	
		90	36.50	21.66	175.0	75.0	−0.92	5.44	
		90	35.57	22.77	150.0	75.0	−0.92	5.44	
East Hellenic Arc Zone		90	34.09	24.78	90.0	47.0	−0.37	2.18	
		90	34.79	26.85	122.0	47.0	−0.47	4.52	
		90	35.01	28.23	100.0	47.0	−0.41	4.24	
		90	36.61	28.71	70.0	47.0	−0.34	3.46	
Cyprian Arc Zone		90	34.24	33.51	100.0	46.7	−0.66	2.04	
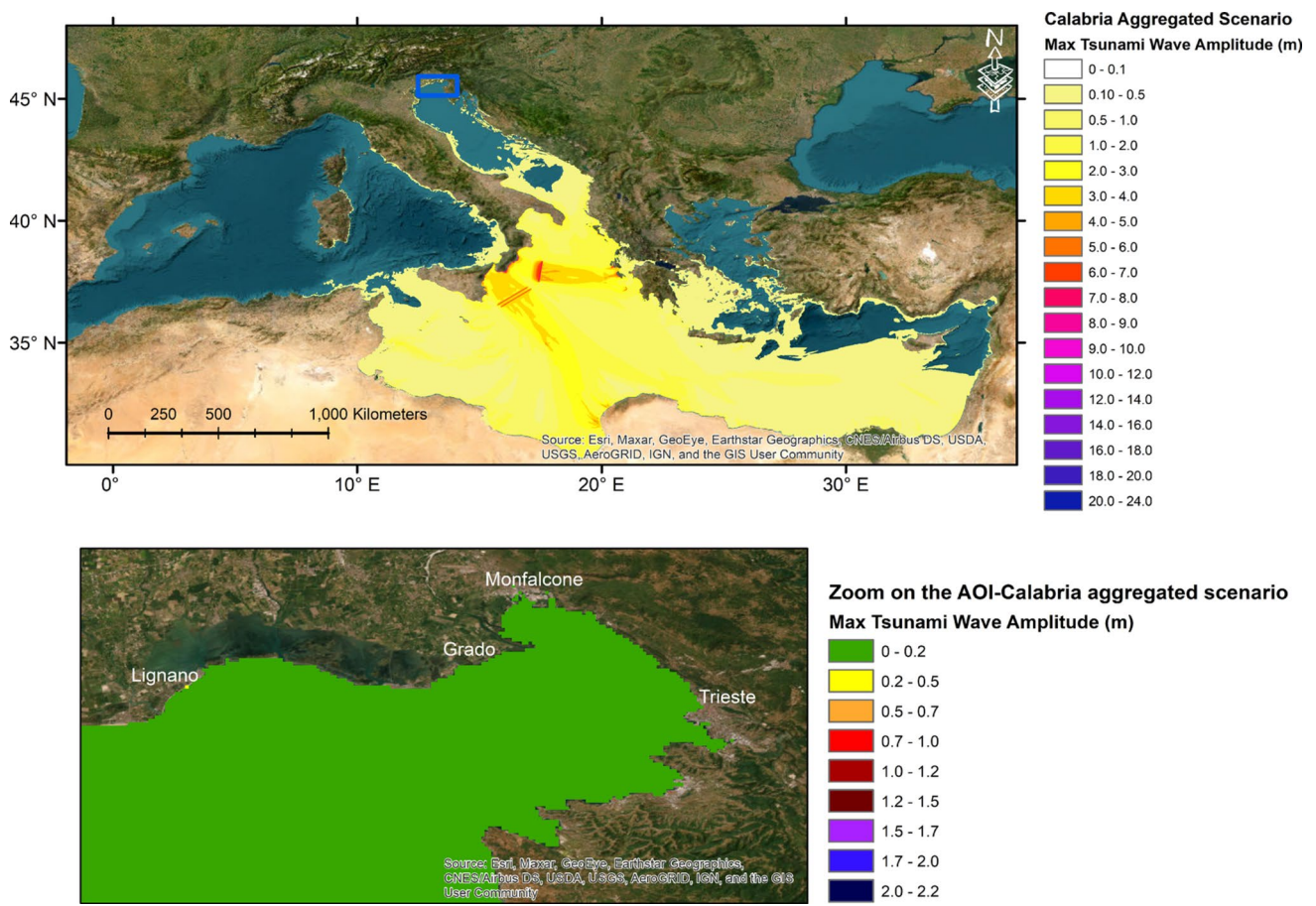
Fig. 12 Aggregated scenario from the individual scenarios (listed in Table 2) computed for the Calabrian Arc zone at basin-wide scale (top) and a zoom on the area of interest (bottom)

the Eurasian Plate and is associated with frequent seismic and volcanic activity. The most famous tsunami event was associated with the M_w8.5 Crete earthquake, an extremely powerful earthquake that occurred on July 21, 365 CE, near the island of Crete in the Eastern Mediterranean. This earthquake and the related tsunami were among the most devastating events in the past, causing widespread destruction across the Mediterranean region. The tsunami had a far-reaching impact, affecting coastal areas in Africa, the Adriatic, Greece and Sicily, as shown by Shaw et al. (2008) and Samaras et al. (2015).

Six individual tsunami scenarios adopted from England et al. (2015) and Hassan et al. (2023) (Table 2) were modelled to evaluate the impact on AOI of possible tsunamis originating within this source zone, which is capable of generating basin-wide tsunamis (Fig. 13). The computed nearshore maximum tsunami wave amplitude at AOI is quite large. It ranges between 0.15 and 0.5 m, which makes this

source the most powerful compared to the other sources outside the Adriatic Sea (Fig. 13, bottom panel).

5.4 East Hellenic Arc zone

The East Hellenic Arc is another subduction zone in the Aegean Sea between Greece and Turkey. Like the West Hellenic Arc, this area is also seismically active and has experienced several significant earthquakes and tsunamis. While the impact of a tsunami from the East Hellenic Arc on AOI is not as high as from other areas, it is still fundamental for authorities and residents in the region to be aware of the potential related risks and take appropriate measures to mitigate them. To this end, an aggregated scenario was computed from three individual scenarios (Table 2) in the East Hellenic Zone (Fig. 14). The maximum computed wave amplitude at the AOI was 0.1–0.16 m (Fig. 14, bottom panel).
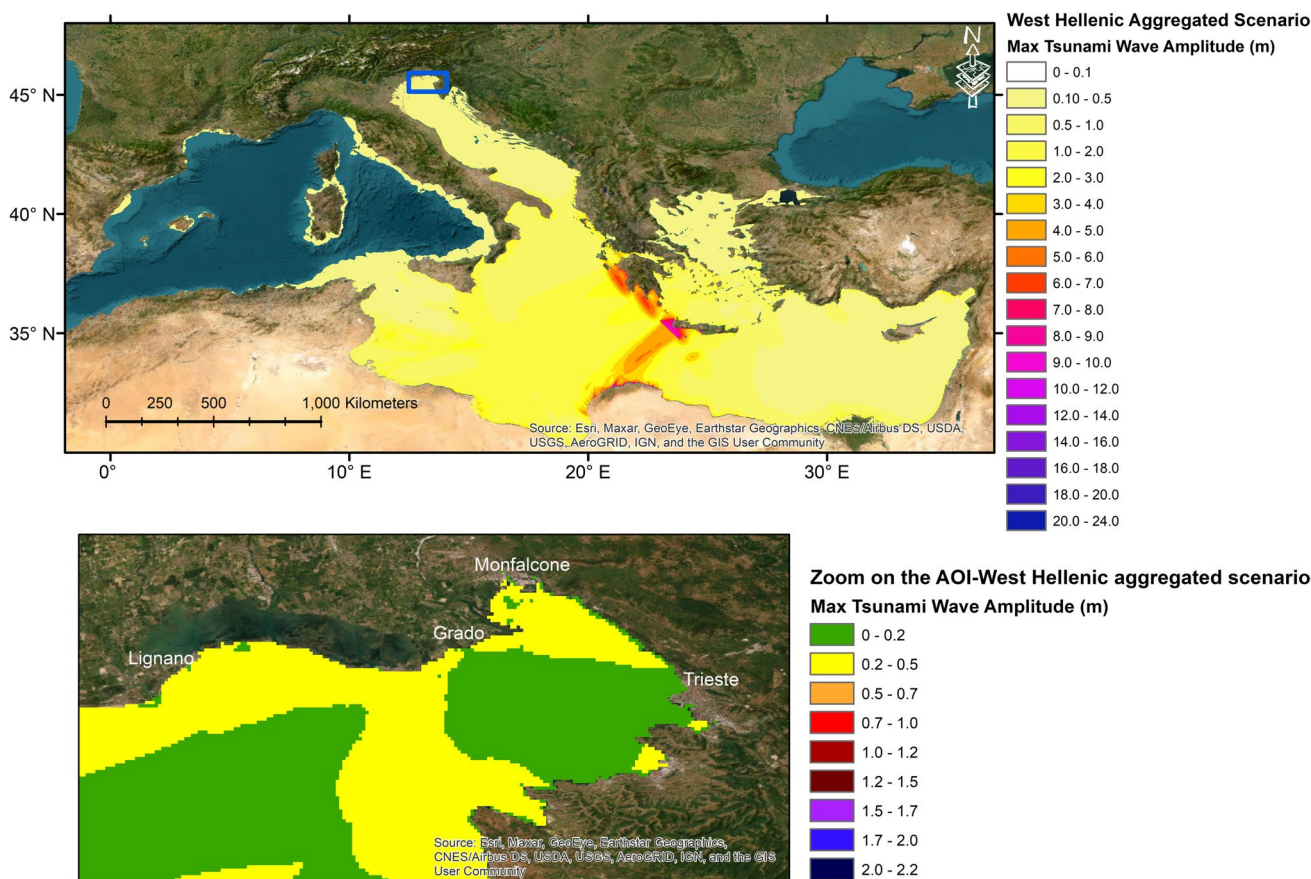
Fig. 13 Aggregated scenario from the individual scenarios (listed in Table 2) computed for the West Hellenic zone at basin-wide scale (top) and a zoom on the area of interest (bottom)
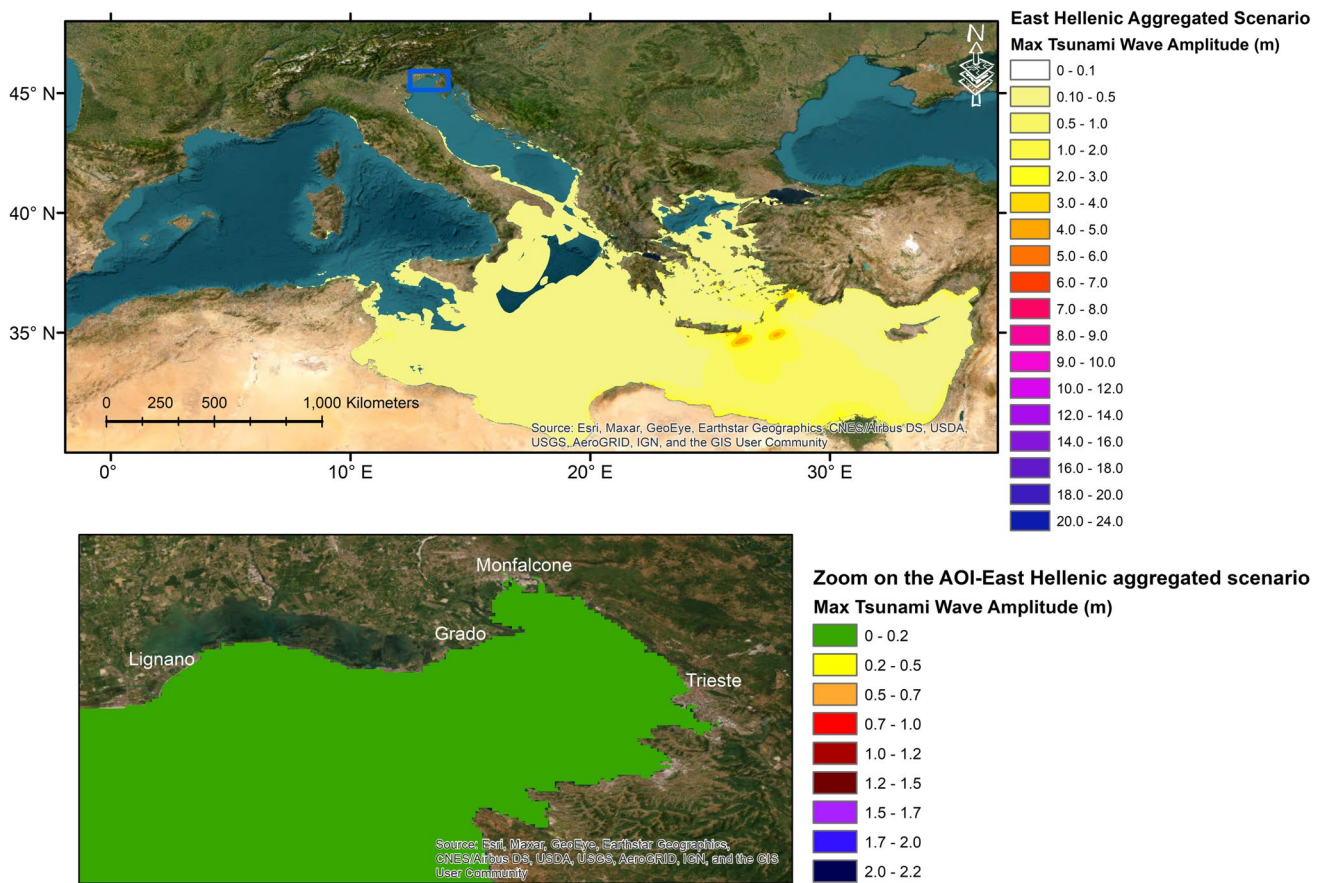
5.5 Cyprian Arc zone

The Cyprian Arc is a subduction zone in the Eastern Mediterranean Sea, between Cyprus and the Turkish coast (Fig. 10). This area is also seismically active and has experienced several significant earthquakes and tsunamis.

While the Adriatic Sea is relatively far from the Cyprian Arc, pre-computed scenarios may still provide useful information for emergency managers in AOI. Overall, the possible impact of a tsunami with origin in the Cyprian Arc on the coast of the AOI proves very low and almost negligible (Fig. 15). The results in Fig. 15 indicate that the tsunami associated with the largest earthquake within this zone (Table 2) might be insignificant (i.e. 0.03 m) in terms of hazard to the AOI.

6 Conclusions and future developments

This work modelled a set of tsunami scenarios, considering all potential seismogenic sources capable of generating tsunamis according to the CAT-INGV's decision matrix. To compute tsunami hazard maps (local, regional and basin-wide), tsunamigenic sources available in the recently updated DISS-3.3 were modelled, indicating a significant increase in the M_{max} of most seismogenic sources. Tsunami maximum wave amplitude, which may enable developing inundation scenarios, was computed over a grid and for the selected POIs, including Trieste, Monfalcone, Lignano and Grado.

Adriatic-wide and regional tsunamis can produce tsunami waves with amplitudes as large as 0.7 and 1.1 m, respectively. Local tsunamis are capable of producing tsunami wave amplitude between 2.0 and 2.2 m; their highest impact could be on the coastal zone of Trieste and Grado,

East Hellenic Aggregated Scenario
Max Tsunami Wave Amplitude (m)

	0 - 0.1
	0.10 - 0.5
	0.5 - 1.0
	1.0 - 2.0
	2.0 - 3.0
	3.0 - 4.0
	4.0 - 5.0
	5.0 - 6.0
	6.0 - 7.0
	7.0 - 8.0
	8.0 - 9.0
	9.0 - 10.0
	10.0 - 12.0
	12.0 - 14.0
	14.0 - 16.0
	16.0 - 18.0
	18.0 - 20.0
	20.0 - 24.0

Zoom on the AOI-East Hellenic aggregated scenario
Max Tsunami Wave Amplitude (m)

	0 - 0.2
	0.2 - 0.5
	0.5 - 0.7
	0.7 - 1.0
	1.0 - 1.2
	1.2 - 1.5
	1.5 - 1.7
	1.7 - 2.0
	2.0 - 2.2

Fig. 14 Aggregated scenario from the individual scenarios (listed in Table 2) computed for the East Hellenic Zone at basin-wide scale (top) and a zoom on the area of interest (bottom)

while it could reach 1.2 m for Monfalcone and about 0.7 m for Lignano, as indicated in Fig. 9 and Tables 3 and 4. The reader should bear in mind that the tables presented here provide just a summary representation of the modelling results. For further details and a comprehensive description of the results, it is necessary to consider the full set of output files (in kml, grid, and dat formats), which contain complete numerical information from the simulations. Detailed analysis of these local sources, as well as the development of more detailed scenarios for the selected AOI, especially in lagoon areas, will be the main focus of future developments.

Basin-wide tsunamis from West Greece, Calabrian Arc and West Hellenic Arc should be taken into account because tsunamigenic earthquakes of $M_{max} > 7.5$ prove capable of impacting the AOI at orange alert level (amplitude less than 0.5 m) and even at red alert level (up to 0.8 m for a magnitude $M = 8.5$ earthquake in the West Hellenic Arc), as

inferred from the modelling. Instead, the scenarios computed for the East Hellenic and Cyprian Arcs provide amplitudes corresponding to the information level.

The modelling results obtained so far provide a primary physics-based description of the tsunami hazard along Northeastern Adriatic coasts, associated with possible tsunamis generated by offshore earthquakes at different epicentral distances. Though the obtained information supplies some quantitative basis in support of the decision-making process, which could be considered if a warning message is issued by the CAT-INGV tsunami alert system, several aspects still need further investigation. To achieve an improved (i.e. more detailed, complete and robust) tsunami hazard assessment, the envisaged future developments include:
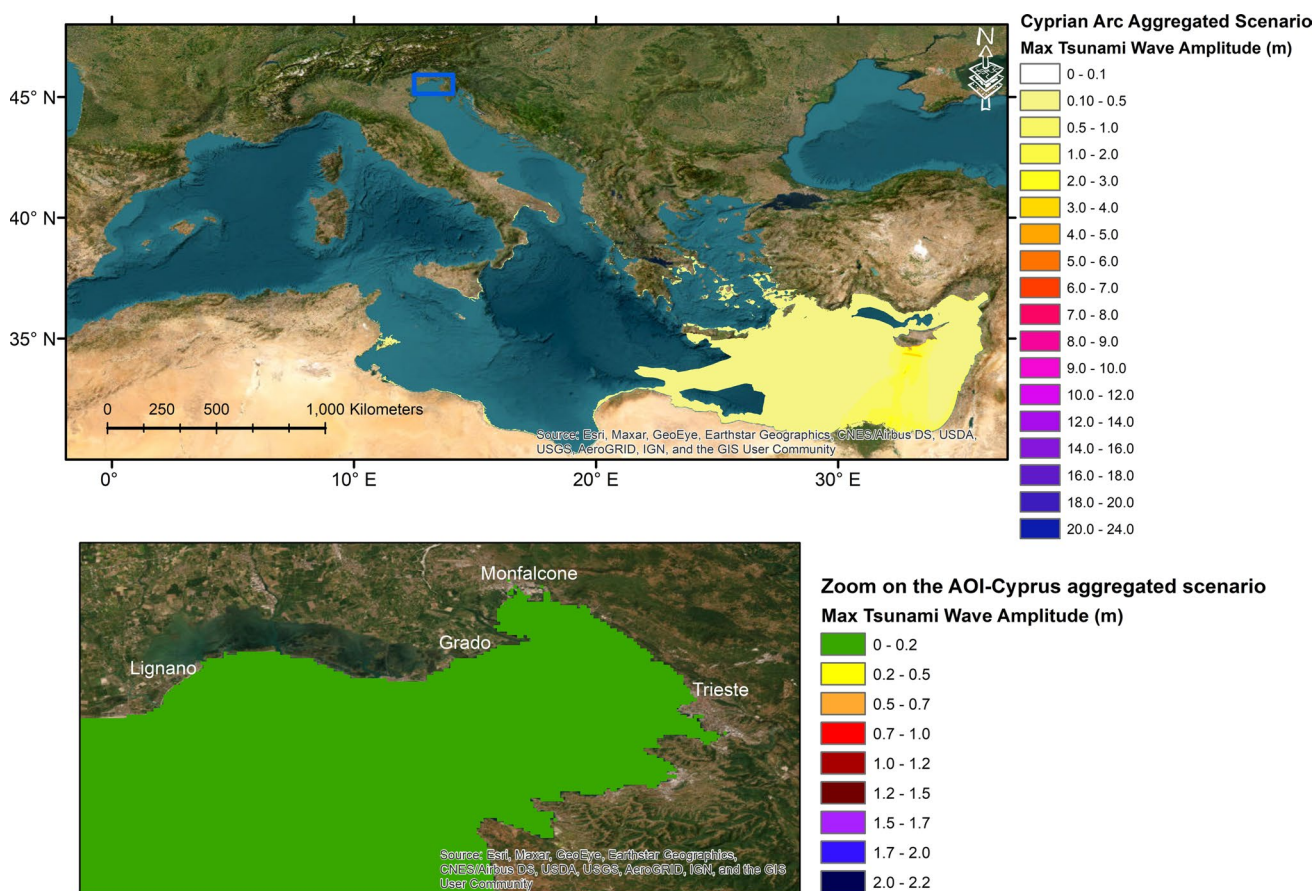
Fig. 15 Aggregated scenario from the individual scenarios (listed in Table 2) computed for the Cyprian Arc Zone at a basin-wide scale (top) and a zoom on the area of interest (bottom)

Table 3 Summary of estimated maximum tsunami wave amplitude (range) at the cities of interest due to tsunami earthquake sources located at the local, regional and Adriatic scales

Location	Local ≤ 100 km H_{max} (m)	Regional > 100 to ≤ 400 km H_{max} (m)	Adriatic-wide > 400 km H_{max} (m)
Lignano	0.6–0.7	0.2–1.1	0.2–0.7
Grado	2.0–2.2	0.2–1.1	0.2–0.7
Monfalcone	1.0–1.2	0.2–0.7	0.1–0.4
Trieste	1.8–2.0	0.2–0.8	0.1–0.4

- In-depth revision of the high-resolution bathymetry dataset to improve the match with observations and to remove possible artefacts (e.g. closed openings and/or channels) which could impact the propagation of tsunami waves within lakes or lagoons behind the shoreline.

- Development of inundation maps by modelling ingression of tsunami waves based upon very high-resolution bathymetry and topography data.
- Sensitivity analysis with respect to M_{max} (including the maximum credible earthquake) to account for the uncertainty on the maximum magnitude associated with the tsunamigenic sources, demonstrated by the recent revision of the DISS database.
- Detailed investigation of local tsunamigenic sources, considering different earthquake rupture styles (i.e. uni-lateral, bilateral), variability and directivity angles, which represent different potential scenarios that may occur in future ruptures.
- Assessment of the hazard from near-offshore tsunamigenic sources, according to guidelines in the decision matrix, taking advantage from earlier studies in the

Table 4 List of estimated maximum tsunami wave amplitude and estimated arrival times (ETA) for the cities of interest associated with the DISS tsunamigenic sources located at the local, regional and Adriatic scales

Class	DISS-ID	Name	Updated DISS-3.3 M_{max}	Maximum tsunami wave amplitude (m)				ETA (min)
				Lignano	Grado	Monfalcone	Trieste	AOI
Adriatic-wide tsunamigenic earthquake sources	ALCS002	Lushnje	7.5	<0.2	<0.2	<0.2	<0.2	394–400
	ALCS020	Seman Coastal	7.2	0.2	<0.2	<0.2	<0.2	400–412
	HRCS001	Mljet	7.3	0.5–0.6	0.4–0.5	<0.2	<0.2	330–340
	HRCS002	Hvar	7.3	>0.2	>0.2	<0.2	<0.2	290–300
	HRCS004	Eastern Adriatic offshore—South	6.9	0.3–0.4	0.2–0.3	<0.2	<0.2	285–295
	HRCS007	Vis-Korcula	7.3	0.5–0.6	0.3–0.4	0.2–0.3	0.2–0.3	260–275
	HRCS010	Palagruza	6.9	0.2–0.3	0.2–0.3	0.2–0.3	0.2–0.3	297–309
	ITCS059	S. Benedetto-Giulianova offshore	7.5	0.2–0.3	0.2–0.3	0.2–0.3	0.2–0.3	230–240
	ITCS074	Shallow Gondola Fault Zone	6.9	0.3–0.4	0.3–0.4	0.2–0.3	0.2–0.3	325–335
	MECS001	Montenegro offshore	8.0	0.6–0.7	0.6–0.7	0.3–0.4	0.3–0.4	296–308
	MECS007	Budva offshore	7.1	0.3–0.4	0.3–0.4	0.2–0.3	0.2–0.3	296–308
Regional tsunamigenic earthquake sources	HRCS008	Dugi Otok	7.5	**1.0–1.1**	**0.8–0.9**	**0.4–0.5**	0.4–0.5	122–135
	HRCS014	Jana-1	6.9	0.2–0.3	0.2–0.3	0.2–0.3	0.2–0.3	244–255
	HRCS018	Vis-West	6.9	0.2–0.3	0.2–0.3	0.2–0.3	0.2–0.3	260–270
	HRCS020	Eastern Adriatic offshore—Central	6.9	0.4–0.5	0.3–0.4	0.2–0.3	0.2–0.3	220–230
	HRCS021	Eastern Adriatic offshore—North	6.9	**1.0–1.1**	0.6–0.7	0.3–0.4	0.3–0.4	95–110
	HRCS025	Krk	7.2	<0.2	<0.2	<0.2	<0.2	168–180
	ITCS004	Castelluccio dei Sauri-Trani	7.3	<0.2	<0.2	<0.2	<0.2	325–335
	ITCS031	Conero offshore	6.6	0.6–0.7	0.6–0.7	**0.6–0.7**	**0.6–0.7**	168–178
	ITCS039	Riminese onshore	7.0	**1.0–1.1**	**1.0–1.1**	0.3–0.4	**0.7–0.8**	155–165
	ITCS070 and ITCS074	Shallow and Deep Gondola Fault Zone	6.9–7.2	0.3–0.4	0.3–0.4	0.2–0.3	0.2–0.3	325–335
	ITCS106	Pesaro mare-Cornelia	6.5	0.2–0.3	0.2	<0.2	<0.2	162–172
	ITCS108	Clara	6.5	0.2–0.3	0.2	<0.2	<0.2	162–172
	ITCS134	Roseto degli Abruzzi	6.9	<0.2	<0.2	<0.2	<0.2	247–257
	ITCS154	Edmond	6.8	<0.2	<0.2	<0.2	<0.2	248–258
	ITCS155	Daniel	6.5	<0.2	<0.2	<0.2	<0.2	194–216
	ITCS158	Valeria	**6.6**	0.2–0.3	0.2–0.3	<0.2	<0.2	194–216
Local tsunamigenic earthquake sources	ITCS100 and ITCS101	Northern Trieste Gulf	6.9	0.6–0.7	**2.0–2.2**	**1.0–1.2**	**1.8–2.0**	15[a]
		Southern Trieste Gulf	6.5					10[a]

The largest wave amplitudes estimated at each city are highlighted in bold

[a] The ETA is too short

region (e.g. Paulatto et al. 2007) and theoretical considerations (Yanovskaya et al. 2003).

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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