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Marine hazards, coastal vulnerability, risk (mis)perceptions – a Mediterranean perspective

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A collection founded and edited by Frédéric Briand.

Marine hazards and coastal vulnerabilities in the Mediterranean – realities and misperceptions

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This article was first sketched during the course of an immersive CIESM Workshop that took place in Istanbul in early December 2023. Developed in the months thereafter on the basis of written exchanges among the participants, it carefully synthesises the main lessons derived from this stimulating exercise and serves as the opening chapter of volume 52 of the CIESM Monographs Series. The authors are grateful to Annelyse Gastaldi for carefully and patiently overseeing the physical production of the Monograph at CIESM headquarters.

1. BACKGROUND

The Mediterranean is the most geologically active maritime region of Europe, sitting on a complex tectonic boundary zone between the European and African plates, and hosting an array of environmental processes that give rise to marine geohazards. While the geology of the region – with the presence of plate boundaries and active faults – makes it prone to relatively frequent earthquakes, tsunamis and submarine landslides, climate change intensifies the frequency and impacts of storm surges and coastal flooding (IPCC 2023).

The Mediterranean Basin is also a densely populated region that operates within multiple national jurisdictions without much regional coordination, with a wide range of coastal and offshore infrastructure developments. Such a context makes Mediterranean shores particularly vulnerable to natural hazards, putting human lives and property at risk.

Curiously, despite a very long history of devastating events (see *Brückner 2024), most notably from tsunamis generated by earthquakes, volcanic eruptions or submarine landslides, the impacts of marine geohazards remain widely underestimated in the Mediterranean. Yet seafloor ruptures due to recent faults, active volcanoes, landslides on steep continental slopes, retrogressive erosion at submarine canyon heads are common features along the Levantine, Aegean, Ionian, Tyrrhenian, Ligurian shores (*Chiocci 2024; *Urgeles 2024) – a coastal landscape complicated by increasingly severe storm surges and river flooding from the hinterland (*Međugorac and Pasarić 2024).

While local communities have learned from the past to build resilience in an environment to which they have adapted over generations (*Bertoldo 2024), this delicate balance is now threatened by significant demographic and economic pressures. The intense coastal urbanization, growing maritime traffic, unceasing touristic developments are of particular concern: they do lead to significant, lasting changes in the coastline such as accelerated coastal erosion that require urgent but adapted management measures (*Mohamed 2024).

*****_the asterisk refers to a distinct chapter in this Monograph_

According to the IPCC 2021 scenarios, accelerated sea-level rise and more frequent storminess, both projected to increase in the future, are now the main drivers of coastal erosion and flooding of low-lying coastal areas. In densely populated coastal areas, groundwater extraction, sediment compaction and land subsidence due to infrastructure construction do constitute additional threats.

Box 1: Definitions of key terms

HAZARD[1]: A process, phenomenon or human activity that, in a given span of time, may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards may be natural, anthropogenic or socionatural in origin. 'Natech' qualifies a natural hazard whose effect is amplified by technological infrastructures (e.g., flooding of power and chemical plant).

RISK[2]: The natural scientific and actuarial concept of risk is based on the coupling of natural hazard and vulnerability in the form "risk = hazard x vulnerability x exposure". Accordingly, risk is understood as the probability of damage to vulnerable people and their property (fatalities, injuries, property damage, economic losses, environmental damage) resulting from an event.

DISASTER[1]: A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts. Annotation: the effect of the disaster can be immediate and localized, but is often widespread and could last for a long period of time.

DISASTER RISK[1]: The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity. Annotation: the definition of disaster risk reflects the concept of hazardous events and disasters as the outcome of continuously present conditions of risk.

NATURAL CATASTROPHE[2]: A serious disruption and severe change in the activities, tasks and objectives of a society due to the actual occurrence of an 'extreme' natural process. The effects lead to extensive material, economic or environmental damage with massive social consequences. The decisive factor in natural catastrophes is that the affected society is no longer able to overcome the crisis with its own resources and outside help is required. The term 'extreme' refers of course only to the human viewpoint.

VULNERABILITY[1]: The conditions determined by physical, social, economic and environmental factors or processes which define the susceptibility of an individual, a community, assets or systems to the impacts of hazards.

N.B. A natural hazard can be differentiated according to the following factors: frequency (temporal frequency, low-high), magnitude (mass or energy transfer, low-high), duration (short-long), spatial extent (limited-large), speed of process build-up (slow-fast), spatial distribution (distribution pattern, punctual-diffuse), and temporal variation (cyclical-stochastic).

[1] Source: UNDRR - United Nations Office for Disaster Risk Reduction, https://www.undrr.org/terminology (accessed: 12 Jan 2024)

[2] Source: Dikau *et al.* 2009

2. The Mediterranean context of geohazards

As expressed in Figure 1, the active geology and the high density of coastal human settlements and infrastructures make the Mediterranean region very vulnerable to marine geohazards. No surprise then if this semi-enclosed basin has the longest historical record of devastating events linked to earthquakes, tsunamis, eruptions and submarine landslides.

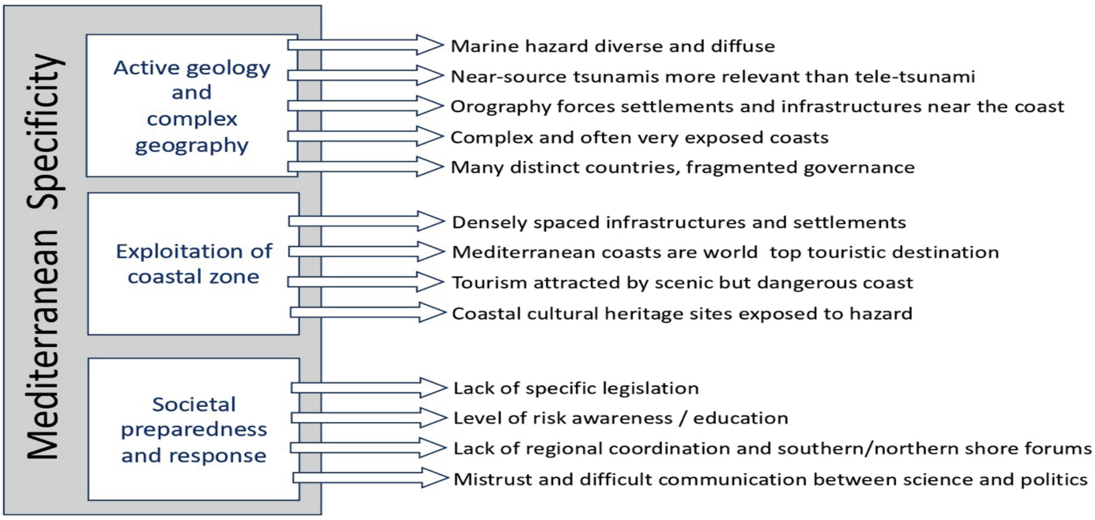


Figure 1. Main markers of marine geohazards in the Mediterranean region.

2.1. Geology and geomorphology

Given its very active geodynamic setting, the Mediterranean region is characterized by high seismicity, volcanism, tectonic seafloor deformation and uplift, plus a range of seafloor sedimentary processes that over historical timescales have repeatedly demonstrated their capacity to generate catastrophic marine events.

Seismicity and volcanism have well-known direct consequences on land and are equally devastating offshore, where they may easily trigger slope failures. In the oceanic domain, these failures may take place on negligible slopes (<1˚) and affect vast seabed areas; moreover, they usually retrograde upslope to affect the coastal zone. In addition, rapid seafloor deformation, induced by faulting, volcanic activity and/or slope failure may generate tsunami waves, which can travel great distances and have catastrophic consequences for coastal zones (e.g. the 1908 events in the Messina Strait that together caused over 70,000 casualties). Most tsunamis in the Mediterranean are triggered by earthquakes, submarine landslides, volcanic eruptions and the collapse of coastal cliffs or volcanic flanks (see *Chiocci 2024; *Urgeles 2024; *Brückner 2024). After the Pacific Ocean, the Mediterranean constitutes the second highest source of tsunamis in the world, with 98 large tsunamis observed in historical times. Every century on average a tsunami of disastrous proportions takes place in the Mediterranean Sea (Papadopoulos 2016). Smaller tsunamis such as those generated by landslides are common and often escape historical reports: such is the case of Stromboli (one of many small Mediterranean islands) where recent analyses point to several tsunamis over the 20th century (Maramai *et al.* 2005). On a longer time scale, sedimentary records indicate that the Mediterranean region has experienced many large catastrophic events involving tsunamis, volcanism, and cliff failures (Papadopoulos *et al.* 2014; Urgeles and Camerlinghi 2013).

While seismicity is widespread in the Mediterranean region, the eastern Mediterranean and in particular the Aegean and Marmara seas are most active in that regard (for details see the map in *Brückner 2024 which illustrates the historical distribution of significant earthquake-triggered tsunamis in the broad Mediterranean Basin).

2.2. Marine climate and oceanography

The Mediterranean Sea generally has a mild climate, though marked winter storms often occur. The maximum recorded significant wave height reaches 10 m, with estimates suggesting even larger values for some undocumented storms. The winter mean significant wave height ranges from approximately 0.8 to 2 m, with the Gulf of Lion in the Western Mediterranean experiencing the largest values (Cavaleri 2005). Wave dynamics in the Mediterranean is primarily influenced by regional orographic conformation and fetch (Lionello and Sanna 2005). Tidal currents are only significant near major passages (e.g., Strait of Gibraltar, Sicily Channel), some smaller passages (e.g., Strait of Messina) and in the Adriatic Sea (Janeković and Kuzmić 2005). Elsewhere, tidal currents are generally just a few mm per second (Albérola *et al.* 1995). Tidal amplitude rarely exceeds 0.5 m, except in the Gulf of Gabes (up to 1.5 m) and in the northern Adriatic (~0.6 m) due to the interaction of tidal wave and bathymetry (Tsimplis *et al*. 1995).
The semi-enclosed Mediterranean Sea is characterized by evaporation exceeding precipitation and river runoff (Millot and Taupier-Letage 2005a). This imbalance causes a difference in water level between the Mediterranean Sea and the Atlantic Ocean, leading to a surface inflow of Atlantic Water into the Mediterranean. The incoming Atlantic Water is continuously modified through interactions with the atmosphere and mixing with older surface Atlantic Water and underlying waters. Sinking and deep-water formation occur in specific zones, typically in the northern parts of the basins, where deep dense water convection takes place. Due to the Coriolis Effect, waters circulating at basin scale (at all depths) tend to follow the isobaths corresponding to their density level in a counterclockwise direction (Millot and Taupier-Letage 2005b). On the northern Mediterranean continental shelves (e.g., Gulf of Lion, northern Adriatic, northern Aegean), waters are significantly cooled during winter as the reduced depth limits heat retention. Despite the buoyancy increase from freshwater inputs via river runoff, dense waters are generated on these northern shelves. These dense waters travel along the shelf and cascade to greater depths, primarily through submarine canyons, until they reach their density equilibrium level (Durrieu de Madron *et al.* 2005).

2.3. Coastal / island populations at risk

According to the records kept by the UN Office for Disaster Risk Reduction (see CRED / UNISDR 2020), human fatalities and serious injuries due to geophysical events (mostly earthquakes and associated tsunamis), or to climate-related disasters (mostly storms, floods, droughts) are now counted in millions every year, while economic losses reach billions of dollars. The Mediterranean population, which lives for a large part in coastal areas at increasing risk of flooding from storm surges, high river discharge, or even tsunamis, is obviously concerned (see Vousdoukas *et al*. 2017).

The Mediterranean region boasts 46,000 km of densely populated shores. At the crossroad of three continents, Mediterranean trade and demographic trends drive increased maritime transport, leading to heightened use of harbors, coastal facilities, and associated developments.

With a rich, long history of human settlement, the region is dotted with numerous coastal towns and villages, and some 200 inhabited islands, together home to almost 9 million islanders. By recent estimates, in the Mediterranean Basin some 100 million people live close to the coast all year around - a number that is at least multiplied by four in the summer months as the Mediterranean remains the world' largest tourist destination. During the summer season, crowded beaches, cruise liners, and private yachts are ubiquitous along the shores. In 2019, just prior to the Covid pandemic, the Mediterranean region received 386 million international tourist arrivals according to UNWTO- the World Tourism Organization. More recent numbers indicate a return to pre-pandemic levels, with continuing increases driven by improved travel infrastructure and a growing middle class.

2.4. Infrastructures at risk

Coastal zones are prime areas for the development of civil infrastructure and large industrial plants in need of maritime access and cooling water. In regions where mountain ranges meet the sea, transport infrastructure like railways, highways, and even airports are often constructed close to the coast. In addition, the region hosts a variety of offshore industries, leading to a growing number of seafloor installations from coastal areas to deep waters. The expansion of trade between Europe, Asia, and Africa causes increasing maritime traffic in the Mediterranean Sea. This maritime transport necessitates secure routes, harbors and associated coastal infrastructure such as shipyards, maritime terminals, storage facilities, piers and jetties.

As of 2010, almost 65,000 km of submarine cables were operational in the Mediterranean Sea. While fiber optic cables exchange data among countries and continents, power cables transfer electricity from the mainland to islands like Sardinia, Corsica, and Mallorca, and connect Albania to Italy. Long distance pipelines also connect different Mediterranean shores. They are all vulnerable to undersea earthquakes and to submarine landslides that can break or damage them.

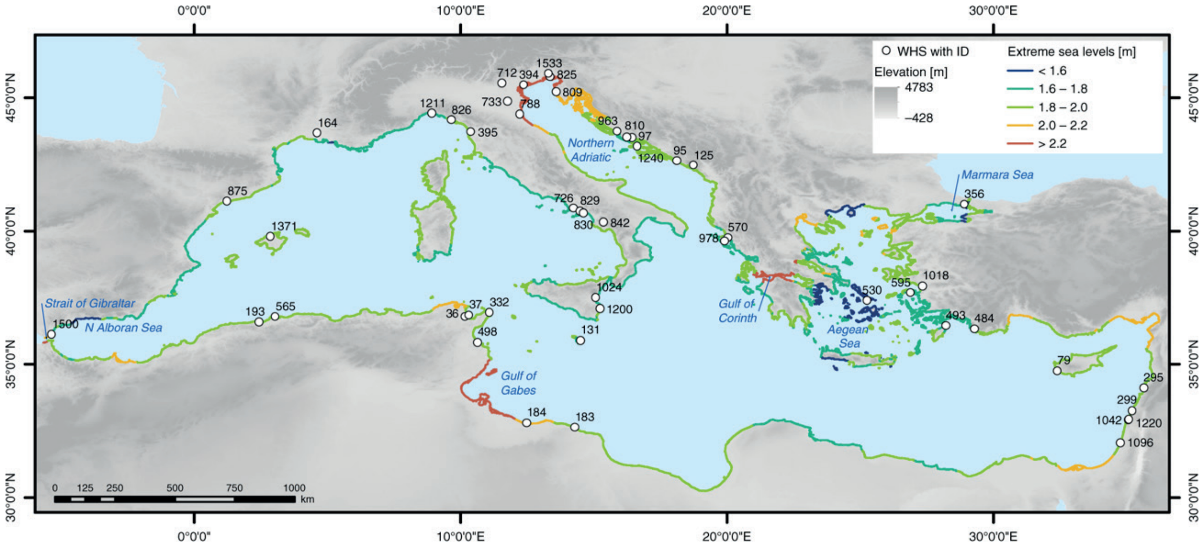
The offshore exploration of mineral resources on or below the sea floor is another cause for concern. The Mediterranean offshore hydrocarbon production contributes nearly 5% of global oil reserves. While current production and development contracts cover only 1% of the Mediterranean sea bottom - mainly concentrated in the Adriatic Sea, Sicily Channel, Nile Delta, and off Cyprus - oil and gas exploration contracts encompass 23% of the sea floor, and areas designated by governments as open for tenders add another 21%.

Field tests in the Mediterranean Sea, specifically in the Tyrrhenian and Aegean seas, have investigated ore-bearing deposits from submarine volcanic activity. Additionally, marine aggregate extraction on continental shelves is increasing, particularly for relict sand deposits used in beach nourishment for retreating coasts.

2.5. A vulnerable cultural heritage

The Mediterranean is one of the few regions in the world with a long and continuous historical/geographical record, that has been documented since ancient times by prominent authors such as Herodotus, Strabo and Pliny the Elder. From an historical perspective, a major, long-term natural hazard that led to the demise of many former ports (Ephesus, Carthage, Ostia antica) is siltation (*Brückner 2024). In most cases their fate was sealed when the delta of the river bypassed them and the harbours silted up. Despite desperate attempts not to lose contact with the sea, the harbours had to be abandoned in the end.

Now that sea levels are rising at a rate faster than in the 20th century and that changing weather patterns enhance the probability of coastal flooding (Bevacqua *et al.* 2020) and extreme wave events (Meucci *et al.* 2020), growing attention is given to the near-term fate of coastal cities dating from the Greek and Roman empires, often located within a few meters of the current coastline.



36 Medina of Tunis
37 Archaeological Site of Carthage
79 Paphos
95 Old City of Dubrovnik
97 Historical Complex of Split with the Palace of Diocletian
125 Natural and Culturo-Historical Region of Kotor
131 City of Valletta
164 Arles, Roman and Romanesque Monuments
183 Archaeological Site of Leptis Magna
184 Archaeological Site of Sabratha
193 Tipasa
295 Byblos
299 Tyre
332 Punic Town of Kerkuane and its Necropolis
356 Historic Areas of Istanbul
394 Venice and its Lagoon
395 Piazza del Duomo, Pisa
484 Xanthos-Letoon
493 Medieval City of Rhodes
498 Medina of Sousse
530 Delos
565 Kasbah of Algiers
570 Butrint
595 Pythagoreion and Heraion of Samos
712 City of Vicenza and the Palladian Villas of the Veneto
726 Historic Centre of Naples
733 Ferrara, City of the Renaissance, and its Po Delta
788 Early Christian Monuments of Ravenna
809 Episcopal Complex of the Euphrasian Basilica in the Historic Centre of Poreč
810 Historic City of Trogir
825 Archaeological Area and the Patriarchal Basilica of Aqui leia
826 Portovenere, Cinque Terre, and the Islands (Palmaria, Tino and Tinetto)
829 Archaeological Areas of Pompei, Herculaneum and Torre Annunziata
830 Costiera Amalfitana
842 Cilento and Vallo di Diano National Park with the Archeological Sites of Paestum and Velia, and the Certosa di Padula
875 Archaeological Ensemble of Tárraco
963 The Cathedral of St James in Šibenik
978 Old Town of Corfu
1018 Ephesus
1024 Late Baroque Towns of the Val di Noto (South -Eastern Sicily)
1042 Old City of Acre
1096 White City of Tel-Aviv --the Modern Movement
1200 Syracuse and the Rocky Necropolis of Pantalica
1211 Genoa: Le Strade Nuove and the system of the Palazzi dei Rolli
1220 Bahá'i Holy Places in Haifa and the Western Galilee
1240 Stari Grad Plain
1371 Cultural Landscape of the Serra de Tramuntana
1500 Gorham's Cave Complex
1533 Venetian Works of Defence between 15th and 17th centuries: Stato da Terra – western Stato da Mar

Figure 2. UNESCO cultural World Heritage sites located in the Mediterranean Low Elevation Coastal Zone. All 49 sites are shown with their official UNESCO ID and name. The map shows extreme sea levels per coastal segment under the high-end sea-level rise scenario in 2100. [source: Reimann *et al*. 2018]

Mediterranean shores host many sites considered of ‘outstanding universal value’ that are listed by UNESCO as World Heritage Sites (WHS). A number of them (49) – mapped on Figure 2 - are situated in the Low Elevation Coastal Zone, with limited protection from rising sea level and flooding hazards. Out of this total, under current conditions (base year 2000), 37 Mediterranean WHS are projected in coming decades to be at risk from flooding - defined as the 100-year storm surge (including tides) - while 42 WHS face a risk of erosion in view of their close proximity to the coastline and of the nature of the sediments (Reimann *et al*. 2018). In the same vein a future scenario integrating projected rises in sea level and increases in storm surges based on IPCC 2021 has been developed for the city of Ampurias - founded around 575 BC by Greeks in what is now northern Catalonia (see *Brückner 2024).

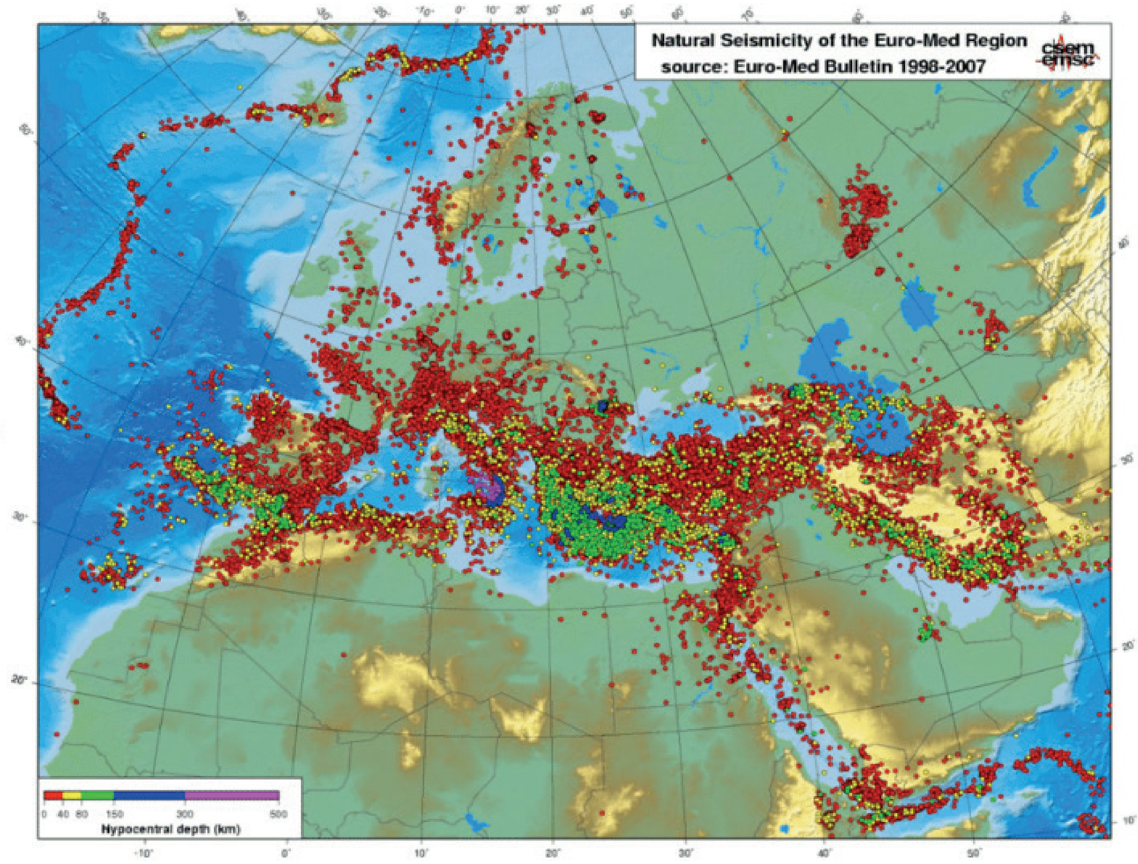
2.6. A fragmented governance

Mediterranean countries display much cultural, linguistic heterogeneity, plus a high level of administrative fragmentation. As a result, communication among neighboring governments, public authorities, industry and research is rarely fluid, with a notable lack of collaboration. For instance, administrative responsibilities for the marine environment are usually divided between regional and national agencies, and often fragmented among various ministries. This division of competencies, compounded by a difficult dialogue between scientists and political level (Briand 2012), unavoidably leads to inefficiencies and difficulties in addressing marine issues comprehensively.

3. GEOHAZARD FREQUENCY vs MAGNITUDE – AN INVERSE RELATION

There is typically an inverse relation between the frequency and the magnitude of geohazards. Thus, events of low intensity (such as minor earthquakes, small landslides, low-level flooding) occur more frequently. For example, small earthquakes can happen hundreds of times a year in a given region. Conversely major earthquakes, large tsunamis, volcanic eruptions occur far less frequently. Understanding this relation is fundamental for risk assessment and preparedness planning, given that rare events will often have catastrophic impacts and that minor but frequent events can have cumulative effects comparable in certain cases to those of major events.

Earthquakes are relatively frequent events in the Mediterranean region (see Fig. 3). They rank among the most damaging geohazards, frequently causing large losses of lives, assets and infrastructure. A most destructive one was the Crete earthquake, with Mw>8, of AD 365 (Ott *et al*. 2021; Shaw *et al*. 2008) which raised the western part of the island by up to 9 m, uplifted and drained the port of Falasarna, and caused a mega-tsunami that destroyed many harbors in the eastern sub-basin. Earthquakes in the Mediterranean region occur not only in compressional settings, but also in extensional settings (e.g., the Gulf of Corinth - one of the fastest spreading rifts in the world) and strike slip settings, with extraordinary evidence of neo-tectonic activity and fluid expulsion at the seafloor in the Marmara Sea (Tryon *et al.* 2012).



Earthquakes hypocentral distribution in the Euro-Med bulletin between 1998 and 2007.

Figure 3. Seismicity in the Mediterranean and adjacent regions (1998-2007). Source: Euro-Med Bulletin.

Submarine landslides do occur in the Mediterranean Sea on magnitude-scales ranging from several 100 km^3 to a few 100 m^3, despite large observational bias towards the smaller events (*Urgeles 2024). Their frequency may vary from several thousand years to a few years respectively. Recent examples of submarine landslides in the Mediterranean Sea, with cascading effects in the form of tsunamis, include the 1954 Algerian margin event (El-Robrini *et al.* 1985), the 1979 event off Nice (Ioualalen *et al*. 2010; Dan *et al*. 2007), the 1977 event at Gioia Tauro (Colantoni *et al.* 1992) and the Stromboli collapse of 2002 (Fornaciai *et al.* 2019; Chiocci *et al*. 2008). None of these landslides exceeded 0.2 km^3 and they can be considered relatively frequent. Much larger events are found in the late Quaternary record.

Volcanic eruptions are not uncommon in the Mediterranean region and have left their mark in historical and archaeological records. The largest include the Thera eruption around 1600 BC, the 217 BC Vesuvius, 44 BC Etna, AD 79 and AD 472 Vesuvius (Stothers and Rampino 1983). Multiple tephra layers have been identified earlier in the upper Quaternary sequence of deep-sea cores from the eastern Mediterranean. These tephra layers appear to be correlated with major source volcanoes such as the Somma-Vesuvius, the Phlegraean Fields, Ischia, Pantelleria, the Aeolian Islands, Mount Etna, and the Aegean arc (Keller *et al.* 1978). The Phlegraean Fields in particular, located near Naples, constitute one of the most significant volcanic systems in the world, with massive eruptions that seem to recur at rates of 10-15 kyrs/event (Sawyer *et al.*

2023), causing widespread devastation and changes to the landscape. In the same sub-basin, volcanoes like Mt. Etna and Stromboli are considered in a state of permanent activity, with frequent eruptions and lava emissions (see Barberi *et al*. 1993) through the past 1500 years.

Tsunamis are usually triggered by earthquakes, volcanic eruptions and submarine landslides (see *Chiocci *et al*. 2024; *Urgeles *et al.* 2024). The zone where the African plate subducts beneath the Eurasian plate, especially near the Hellenic Arc, is a frequent source (Sørensen *et al*. 2012; Tinti *et al*. 2001). The Mediterranean region has experienced several catastrophic tsunamis in the past 2500 years, most of them generated by strong earthquakes (Papadopoulos and Fokaefs 2005). Documented historical examples include the 365 and 1303 tsunamis caused by earthquakes in the Hellenic Arc, and the disastrous 1908 event that destroyed the cities of Messina and Reggio Calabria. Other devastating events occurred in 373 BC and 1748 in the Gulf of Corinth. More recently destructive tsunamis have occurred in the Aegean Sea in 1956 with runup heights reaching 25 m (Papazachos *et al.* 1985) and off the Algerian margin in 2003 (Alasset *et al.* 2006).
There are historical examples of landslide-generated tsunamis in the Mediterranean Sea such as the 1783 Scilla tsunami in the Messina strait (Wang *et al.* 2019; Mazzanti and Bozzano 2011) or, more recently, the 1954 Algerian margin event (El-Robrini *et al.* 1985), the 1979 event off Nice (Ioualalen *et al.* 2010) and the Stromboli collapse of December 2002 (Fornaciai *et al.* 2019). Large tsunamis can also be generated by caldera-forming volcanic eruptions, such as the massive tsunami caused by the eruption of Thera (Santorini) volcano in the southern Aegean Sea around 1600 BC (Friedrich *et al.* 2006) which is widely cited (see Soloviev 1990) as ultimately driving the destruction of the Minoan civilization.

Storm surges, caused by air pressure gradient and wind forcing, may last from several hours to several days. They are more likely to occur in regions with wide continental shelves where winds play a major role in their formation (Toomey *et al.* 2022), and in areas with an extended fetch where wind can considerably build up. In the Mediterranean, they are a major contributor to coastal sea-level extremes, with frequent occurrences along the northern Adriatic, the Aegean coasts and in the Gulf of Gabes (Cid *et al*. 2016; Pérez Gómez *et al*. 2022). There are historical, famous examples of storms which determined the course of naval battles, such as the confrontation between the Persian and Greek fleets in 480 BC, when two storms largely destroyed the Persian fleet (Herodotus 8.1-39).
Other sectors of the Mediterranean coast are less prone to storm surges, but certain areas with low-laying terrain (e.g., the Nile Delta in Egypt, the Ebro Delta in Spain; Hereher 2015; Grases *et al.* 2020) are vulnerable to high flood risk during extreme events. In the northern Adriatic, where storm surges can be superimposed on other sea-level processes, total sea levels can be particularly pronounced, up to nearly 2 m (Marcos *et al*. 2009; Lionello *et al*. 2021).

Meteotsunamis generate waves that can travel at high speeds due to high frequency atmospheric disturbances but are limited to shallower water bodies than standard tsunamis. This phenomenon can be quite sudden, often with little warning, occurring unfrequently (ca. once in a decade) and at specific sites, notably on the eastern Adriatic coast (see Šepić and Orlić 2024). They are localized events that typically arise during the summer months due to specific resonance conditions which involve the coupling of atmospheric forcing with the geomorphological properties of certain bays and harbors. They last from several minutes to an hour, and their amplitudes can attain several meters (Vilibić *et al.* 2021). From 23 to 27 June 2014 a series of meteotsunami waves of long period, up to 2-3 m high, generated by intense small-scale air pressure disturbances and propagating eastward, caused considerable damage from the

Balearic Islands to Odessa (Šepić *et al*. 2015). That was the first documented case of a chain of destructive meteorological tsunamis occurring over a distance of thousands of kilometres. Mediterranean meteotsunamis are events out of the ordinary, at least enough to receive local names- *rissaga* (Balearic Islands), *marrobbio/ marrubbio* (Strait of Sicily), *milghuba* (Maltese Islands), and *šćiga/ štiga* (Adriatic Sea).

Coastal erosion is a significant concern in the Mediterranean Basin, carrying large economic costs. It is the outcome of continuous, complex interactions between natural processes and human activities. Natural processes encompass local conditions (topography, wave dynamics), shoreline dynamics driven by long-term hydrodynamic and geological factors (e.g., loosely consolidated substratum), shoreline retreat due to relative sea-level rise, and episodic erosion during more frequent storms (Pang *et al.* 2023) with intense wind-wave action and higher sediment instability. Human activities (such as construction of harbors, recurrent dredging operations in port areas, coastal infrastructures like seawalls and jetties, flood control works, sand mining) will often disrupt the delivery of sand to the coast and contribute to beach erosion, especially in low-lying, flat coastal areas. Furthermore, all Mediterranean deltas are 'undernourished' and therefore impacted by erosion, as the river sediment is trapped in reservoirs while the river water is extracted for human purposes (drinking water, irrigation of fields).

4. FROM RISK PERCEPTION TO PREPAREDNESS

Risk is mainly the possibility that a hazard is made real. Individuals alone or in communities can shape how they view these possibilities to be able to go about their lives. Risk preparedness is a function of knowledge, experience and perception of such events. As one of the regions with high geohazard potential and most exposed to global warming, with a forecast rise in temperature of 2-3°C by 2050, the Mediterranean Basin is projected to experience an unparallel increase in the frequency of extreme weather events (Vousdoukas *et al.* 2017). An open, important question is whether Mediterranean populations are aware of such imminent risks.

Over generations Mediterranean communities have dealt with painful memories of catastrophic events which still nourish social memories, instead of being forgotten. These social memories contribute to communities' resilience, through increased risk perception and adaptation.

4.1. The memory loss of catastrophic events

In the aftermath of a major natural disaster, the memory of the horror gradually fades and other aspects come to the fore. This applies as well to coastal disasters in the Mediterranean. Take the island of Santorini that is thriving with people today and ranks as a major touristic destination, despite the devastating 'Minoan' eruption around 1600 BC that blew up most of the Thera volcano. Or the Crete earthquake in AD 365 when the tsunami waves that followed destroyed many harbors and coastlines in the eastern Mediterranean. The areas were soon resettled and nowadays hundreds of thousands of tourists enjoy the Cretan beaches every year.

Eruptions of Mt. Vesuvius have been reported on several occasions throughout history, with a major one in 1944 during WWII. The most famous no doubt is that of AD 79 which entirely destroyed the wealthy towns of Pompeii and Herculaneum and passed on to posterity through the letters of Pliny the Younger who lost his illustrious uncle in the tragedy. Yet, despite the destruction and large loss of lives, people later returned to the area and resettled the flanks of the volcano, attracted by the favourable conditions for agriculture. Eventually human memory lost track of the massive eruption and it was not until many centuries later that the well-preserved ruins of Pompei were 'rediscovered' fortuitously under thick layers of ashes and soil by a farmer in the late 16^{th} century.

4.2. Social perception of hazards

Cultures around the Mediterranean deal differently with social memories of past disasters (see *Bertoldo 2024). While some cultures deal with the anxiety created by past events by remembering and planning, others are more comfortable with collective efforts to 'forget'. When public management downplays the possibility of a catastrophic event despite the local knowledge of a risk, a number of studies have described signs of collective anxiety and fatalism (Joffe *et al*. 2013).

It is of course important to make a distinction between low impact / high frequency risks such as storms – that tend to be 'normalized' (see Luís *et al.* 2016) – and risks with high impact / low frequency as tsunamis – which tend to be amplified in social memory.

Therefore, the preservation of social memory - through memorial sites, celebrations, teaching and informative risk awareness sessions - fills an important role in keeping alive risk perception and, at the same time, it reassures communities that they can cope with these risks if/ when they will be hit again.

The societal acceptance of natural hazards and, most importantly, the degree of human preparedness will be much enhanced as more is known about them, about their mechanisms, about their effects on landscapes and societies, and as more is shared among local communities. As a result, information transfer will be optimised and the risk management strategies will be better understood and accepted (Ivčević *et al*. 2021).

As a collective exercise, the workshop participants compared their perceptions of a variety of coastal hazards – from rare to recurrent – that were discussed during the course of this workshop. The subjective outcome, purely qualitative, is illustrated in Figure 4, in the form of a 3-D diagram and in Figures 5A and 5B, as 2-D diagrams, where geohazards are positioned as a function of their recurrence, perceived level of economic destruction, and their degree of public recognition/ perception.

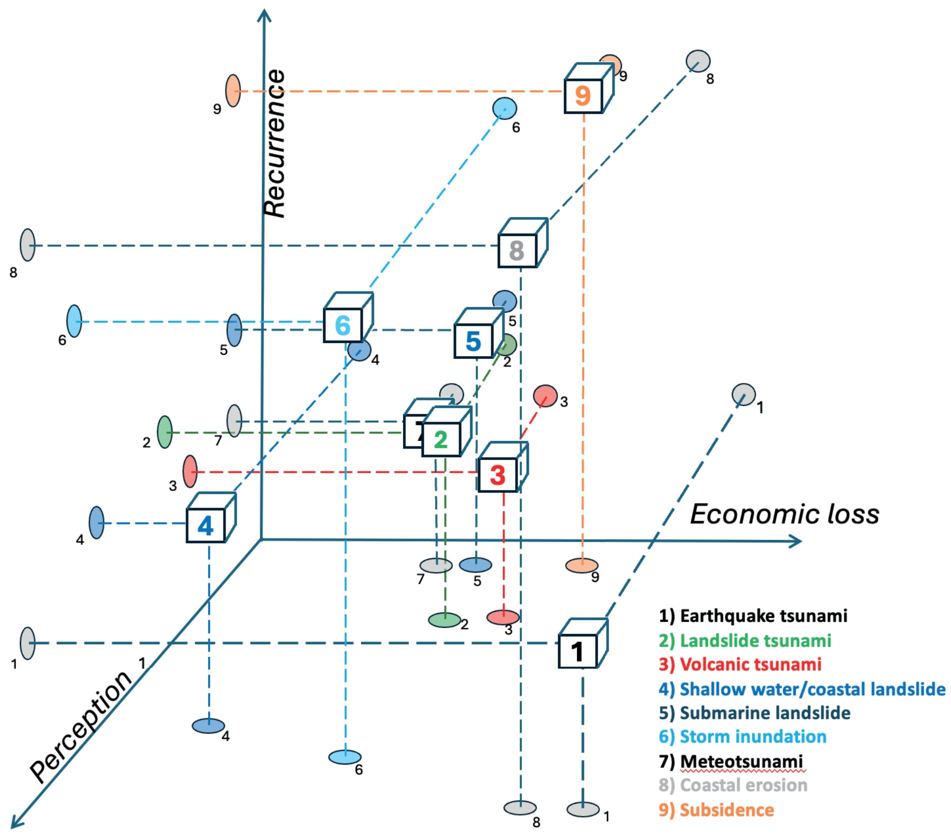


Figure 4. Level of perception of coastal geohazards, their economic impact, their frequency in 3D

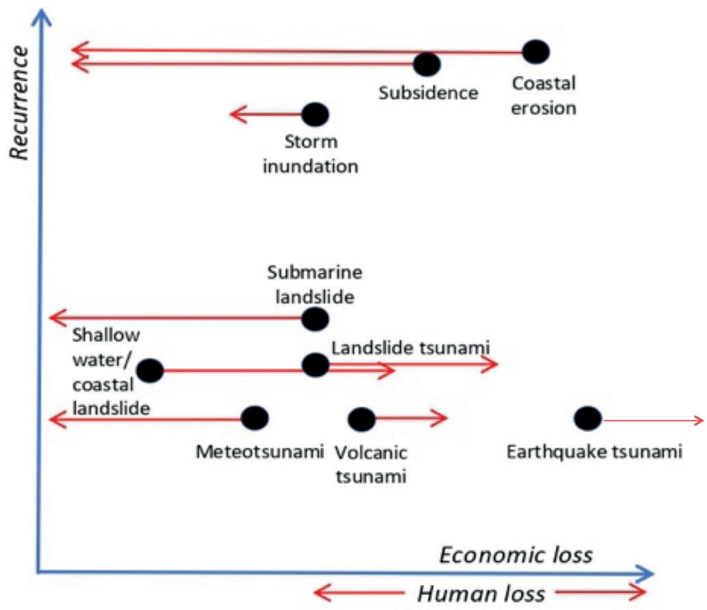


Figure 5A. XY diagram of Figure 4, which indicates the economic loss generated by geohazards of different frequency/ magnitude. The red arrows signal how the "damage" increases or decreases when human loss, instead of economic loss, is taken into account.

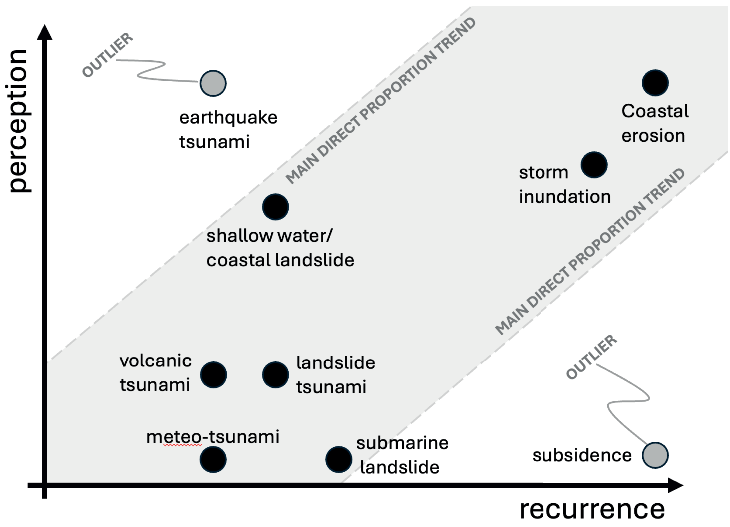


Figure 5B. YZ diagram of Figure 4, which illustrates the general relation between the level of perception of geohazards and their frequency.

The direct increase (shaded area) between perception and recurrence is not unexpected as the most frequent hazards are more easily recognized than rare ones, but there are two interesting outliers. The first is subsidence: while very frequent (in deltas, coastal plains, etc.), subsidence remains broadly ignored even if it drives coastal erosion, salinization of groundwater, and high risks for infrastructures. The other outlier - tsunami generated by earthquake – benefits from a high global recognition although it is a very rare event. Millions of people worldwide have seen on television the catastrophic images of the 2004 Indian Ocean tsunami and of the 2011 Tōhoku tsunami that devastated the eastern coast of Japan and the Fukushima nuclear plant.

4.3. Management / mitigation of coastal hazards

Distinct human societies face diverse risks and will not necessarily have the same level of local awareness about the potential natural disasters confronting them. But all deserve to receive the best possible information. The 2004 Indian Ocean tsunami suddenly raised awareness of the possibility of tsunamis in several Mediterranean countries. Countries with high seismicity, such as Greece and Turkey, were particularly alarmed. Subsequently tsunami warning signs and designated evacuation routes (see Figure 6) were erected in a number of vulnerable locations. But local tsunamis can also be triggered by submarine landslides, or collapses of volcano flanks which are much more difficult to foresee.

Figure 6. Tsunami warning signs: left in Stromboli Island (source: https://www.esvaso.it) - right : at a gate of the old city wall in Istanbul Fatih District (source: H. Brückner)

We have days of warning before a major storm surge, and so we can prepare and evacuate. Even volcanic eruptions have warning signs at least a few hours or even days in advance. Further, social media and mobile phone applications can relay such alerts fast and wide.

However, the same cannot be said for earthquakes and the tsunamis they may generate. We know that the Hellenic Arc and the North Anatolian Fault Zone can become active at any time, with devastating consequences. Cliff collapses and submarine landslides can also happen quickly. Even if a well-functioning early warning system were in place, the time required for tsunami waves to hit Mediterranean coasts would be short – in all cases less than one hour, and often much less.

On the other hand, there is a variety of solutions available to mitigate the effects of the anticipated sea-level rise and protect residents and socioeconomic activities in vulnerable coastal areas. They range, as seen in Figure 7, from coastline retreat, accommodation, advances into the sea, coastal protection, to ecosystem-based adaptation. The most appropriate strategy will depend of the local social and legal context which is often challenging.

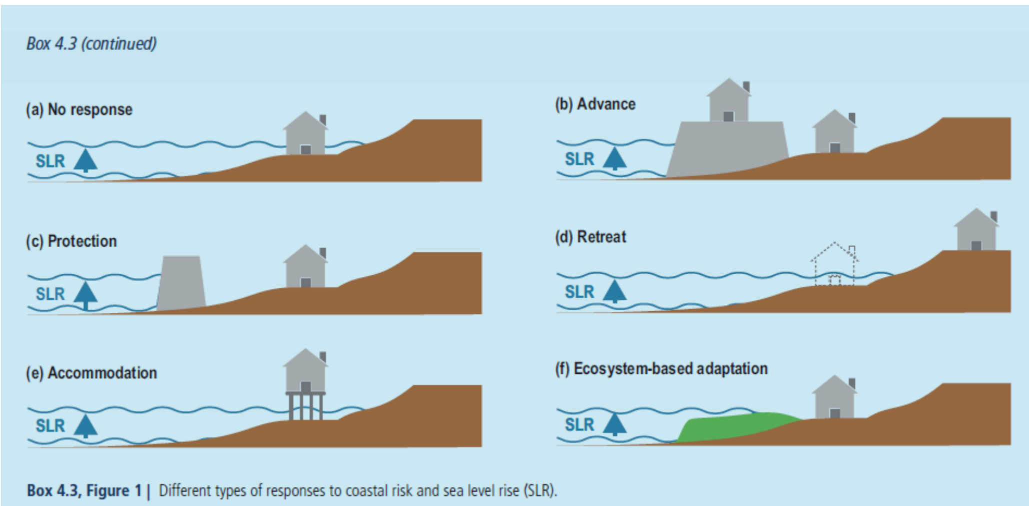


Figure 7. The various responses to risks associated with sea level rise. [Source: IPCC 2019]

When the *retreat option* is chosen, the coastal area does not receive marine protection. In the worst-case scenario, an entire coastal region can be destroyed. In highly populated areas hosting a range of socioeconomic activities, retreat is not an option and *accommodation* measures need to be implemented so as to reduce coastal risk and impacts on the residents, human activities, ecosystems, and the built-in environment. Measures will include building codes, elevation changes, land use changes, and institutional responses like Emergency Warning Systems, insurance schemes, and setback zones. Under the *protection option*, combined hard and soft stabilization measures are implemented: the shoreline is protected from the sea by the construction of solid structures including rock revetments, sea walls, and breakwaters, and dunes are used as soft solutions to stabilize the coast. The *ecosystem-based option* reduces coastal risks by creating new land by building seaward, reducing coastal risks. This includes land reclamation, landfilling, planting vegetation, and polarization, requiring drainage and pumping systems.

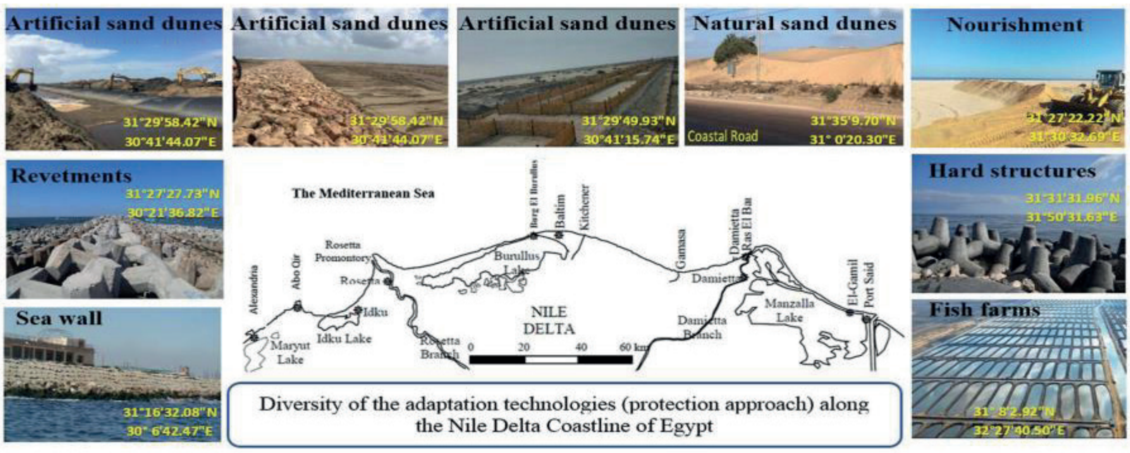


Figure 8. Adaptation technologies along the Nile Delta coastline (after Mohamed and Abd-El-Mooty, 2023).

The mitigation of coastal erosion will involve a combination of such natural and engineered solutions, from beach nourishment, dune restoration and the construction of coastal protection structures. In the highly impacted Nile Delta coastal zone (see Fig. 8), good practices and adaptation strategies include limiting construction in risky areas, rebuilding coastal sand belts and dunes, maintaining wetlands, modifying land use, shifting infrastructure, monitoring water extraction, together with monitoring programs and early warning systems.

4.4. Projected trends

With the projected increase in sea level (IPCC 2023) it is easy to predict an intensification of marine natural hazards and increasing coastal vulnerability in coming decades. Zones already affected by coastal storms, flooding, and erosion will be each year more impacted. As illustrated in Figure 9, climate change will be a significant actor indeed, but not necessarily the main one: as coastal urbanization will intensify, human pressure and demand for energy, groundwater, harbors, transport, etc. will only grow, making populations even more vulnerable and exposed to marine geohazards, with largely lagging legislation and rare mitigating measures.

The action of sea level rise (itself induced by human activities) will be compounded by direct human intervention. In recent decades already, the trend of continued delta progradation has been reversed: the construction of reservoirs and the extraction of water for drinking and irrigation have led to a significant transgression and ingression of the sea, resulting in further coastal erosion and salinization of aquifers. The latter effects are exacerbated by sea-level rise and storminess. These two factors will only accelerate in the future, affecting all coasts worldwide and leading to increased coastal erosion. Low-lying coasts and areas undergoing tectonic subsidence are particularly at risk. Mediterranean deltas in particular will all suffer from erosion, subsidence and salinization.

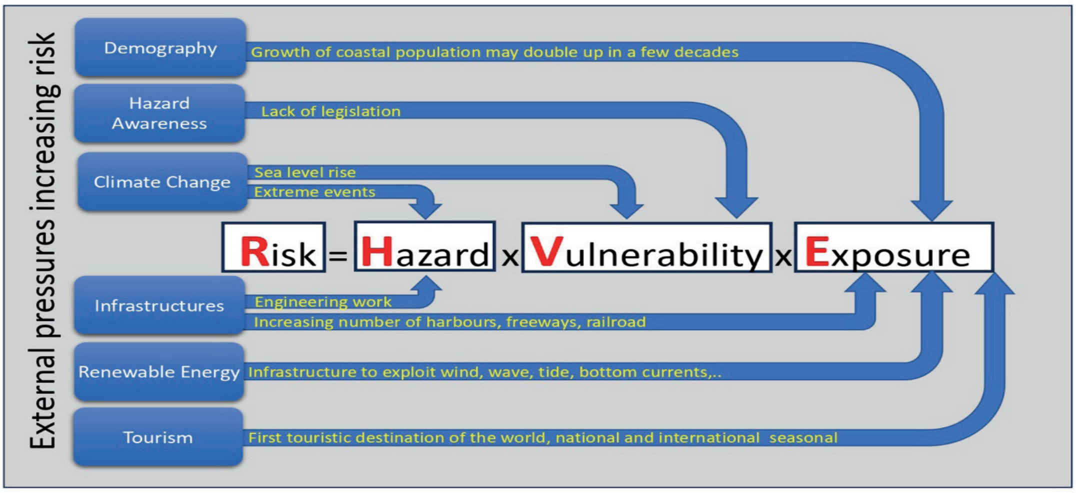


Figure 9. Synthetic diagram of why the risk for coastal communities and infrastructures is bound to increase in the near future, in response to different environmental/anthropic pressures**.**

On a longer time scale, the potential effects of major global climatic changes on rare events such as earthquakes, submarine landslides and tsunamis remain scientifically hard to determine and predict. Evidence from the geological record and numerical models suggests that on the short/medium term (100 years) significant deviations in the current seismicity rate due to flexural bending stresses (Brothers *et al.* 2013) from recent sea-level rise (estimated at 3.6 mm/yr for the period 2000-2018 (Calafat *et al*. 2022) are not expected.
Given earthquake occurrence rates and the downward propagation of thermal perturbations from global warming that could affect the few gas hydrate reservoirs in the shallow subsurface of the Mediterranean (Archer 2007), it is only in the long term that variations in the trends of submarine landslide occurrence may emerge. No changes are expected in earthquake rates from lithospheric-asthenospheric processes such as subduction earthquakes and derived tsunamis (Sallarès and Ranero 2019) as in the Hellenic Arc.

5. Selected Priorities for Research

Here is a (non-exhaustive) list of research areas that were considered as priorities by the workshop participants:

- Assess the risk of natural hazards for densely populated coasts and for coastal heritage sites in the Mediterranean region.
- Identify Mediterranean coasts where sea level rise is amplified by land subsidence.
- Assess the potential of non-seismic tsunami sources: volcanoes, atmospheric disturbances and landslides.

- Develop probabilistic approaches to tsunami forecasting that include submarine landslides as a source mechanism.
- Explore further the continental margins of the southern Mediterranean in order to better understand the distribution and frequency of natural hazards.
- Analyse when and where do medicanes form. What are the triggering mechanisms?
- Compare the effectiveness of ecosystem-based coastal management strategies to mitigate coastal erosion and enhance resilience.
- Identify high population tsunami risk areas that feature bays of various scales.
- Improve the risk management of off-grid, cascading events: how are such risks anticipated, perceived and managed around the Mediterranean?
- Analyse the societal and cultural implications of natural hazards in coastal Mediterranean communities, in particular the impacts on traditional livelihoods, cultural heritage and community resilience.
- Integrate marine geohazards into land management policies at regional, national, and local levels.

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