Volume XXVII 2024
ISSUE no.1
MBNA Publishing House Constanta 2024

Scientific Bulletin of Naval Academy

SBNA PAPER • OPEN ACCESS

Tsunami Occurrence in the Southern Part of the Black Sea Coast: A Case Study

To cite this article: Andra-T. Nedelcu, Dinu-V. Atodiresei, Romeo Bosneagu, Lucian Dumitrache, Alecu Toma, Sergiu Serban, Sorina Antoche, Scientific Bulletin of Naval Academy, Vol. XXVII 2024, pg. 134-143.

Submitted: 09.05.2024
Revised: 25.06.2024
Accepted: 02.08.2024

Available online at www.anmb.ro

ISSN: 2392-8956; ISSN-L: 1454-864X

doi: 10.21279/1454-864X-24-I1-018

Tsunami Occurrence in the Southern Part of the Black Sea Coast: A Case Study

Andra-Teodora NEDELCU[1], Dinu-Vasile ATODIRESEI[1], Romeo BOSNEAGU[1], Lucian DUMITRACHE[1], Alecu TOMA[1], Sergiu SERBAN[1], Sorina ANTOCHE[1]

[1]Mircea cel Batran Naval Academy, Faculty of Navigation and Naval Transport, 1 Fulgerului, RO-900218, Constanta, Romania
andra.nedelcu@anmb.ro

Abstract. The Black Sea, an enclosed inland sea bordered by six country, known for its historical significance and unique ecological features, has relatively low seismic activity compared to other regions prone to tsunamis. However, the potential for tsunami occurrence in this region cannot be disregarded, particularly in the southern part of the Black Sea coast, particularly along Turkey, where geological and oceanographic conditions might contribute to the generation of tsunamis. This case study aims to investigate a hypothetical scenario of a tsunami striking the southern part of the Black Sea coast, analysing the potential causes, impacts, and mitigation strategies. Understanding these occurrences is crucial for costal management and disaster preparedness.

1. A SHORT HISTORY OF TSUNAMI GENERATION IN THE BLACK SEA

The Black Sea is a unique geological structure, formed through complex tectonic processes involving the convergence of the Eurasian, Anatolian, and Arabian plates. The Black Sea, bordered by six countries including Bulgaria, Romania, Ukraine, Russia, Turkey, and Georgia, is a semi-enclosed body of water connected to the Mediterranean Sea through the Bosporus Strait. The southern coast of the Black Sea lies near the North Anatolian Fault (NAF), a major right-lateral strike-slip fault that is highly seismically active. Earthquakes along this fault can trigger underwater landslides and tectonic shifts, leading to tsunamis. Despite its relatively low seismic activity, the region has experienced tsunamigenic events in the past, albeit infrequently. Historical records indicate instances of tsunamis caused by underwater landslides, seismic activity, or volcanic eruptions [1].

Although considered a rare natural phenomenon, tsunami events in the Black Sea have been generated in the past and some studies show that at least 20 tsunamis have been observed [2].

However, historical records and geological studies reveal that the Black Sea has experienced several significant tsunamis. One of the earliest recorded tsunamis in the Black Sea occurred in 544 AD. Historical accounts describe significant sea level changes and coastal flooding. This event is attributed to seismic activity along the NAF, causing underwater landslides and subsequent tsunamis.[3]

Monitoring of earthquakes in the Black Sea, as well as tsunami modelling scenarios as a result of high magnitude earthquakes, has led to a better understanding of this phenomenon. It is also important to undertake further research to properly understand the phenomena and develop strategies to prevent loss of life and property.

Predicting tsunami waves is extremely difficult. Most historical tsunamis have been triggered at short distances from the coastline. The magnitudes of earthquakes in the Black Sea are not large and the impact is local. Understanding the geological, oceanographic, and socio-economic factors influencing tsunami hazards, stakeholders can develop proactive mitigation strategies to minimize the impacts and enhance the resilience of coastal communities in the region.

2. FACTORS GENERATING TSUNAMIS IN THE BLACK SEA

The main factors generating tsunamis include submarine earthquakes. When tectonic plates move and release a large amount of energy, large waves of water are created and move rapidly towards the shore.

Landslides that occur on underwater slopes of mountains or hillsides can cause sudden movements of water, generating a tsunami. These landslides can be caused by earthquakes, volcanic activity or natural land instability. Landslides in coastal areas and/or wall/rock collapses into the water can also cause tsunamis.

Cosmic object impact: in rare cases, the impact of a cosmic object, such as an asteroid or meteorite, in the ocean can create a tsunami.

3. MARITIME RISK ANALYSIS

Risk is a function of the probability and consequence of a particular hazard occurring. [3] When we refer to risk, we must also consider the two factors involved: the probability of an adverse event occurring and the consequences of the event.

$$R = P \times C \tag{1}$$

Where: R-risk; P-probability; C-consequence.

Hazard is a potential source of harm to humans, the environment and society. Events or circumstances constitute hazards when their nature would allow them, even theoretically, to cause harm to health, life, property or any other valuable interest.

Maritime risk refers to future but uncertain events that may occur during navigation at sea, causing damage or loss of goods carried. Circumstances or events that endanger military ships are determined by the following risks, from a hydrometeorological point of view:

- Storm: phenomenon related to high intensity atmospheric turbulence, characterised by strong winds and extremely high waves, which can cause damage to goods due to water entering the ship's compartments;
- Shipwreck: ship sinks due to major weather phenomena (waves, wind, electrical discharge, etc.);
- Ship collision: a collision between two ships or ships with floating infrastructure or parts (breakwaters, wrecks, icebergs, etc.);
- Fire: fires from damaged tanks or gas pipelines;
- Explosion: a sudden reaction of oxidation or decomposition with an increase in temperature, pressure or both; produced in the presence of a flammable material;
- Contamination of drinking water;
- Flooding.

The paper analyses the meteorological factors in the occurrence of a tsunami in the southern part of the Black Sea coast.

In Table 1. different types of hazards and the effects/damage produced by tsunami are presented.

Tabel.1 Hazards

Nr.	HAZARDS	Tsunami effects/damage
1	**WEIGHT**	Tsunamis are generally smaller than those in the open oceans, due to the small size and shallow depth of the Black Sea.
2.	**WAVE VELOCITY**	The propagation speed of a tsunami depends on the depth of the water and the distance from the tsunami source. Tsunamis travel at high speeds of hundreds of kilometres per hour. However, in the Black Sea, shorter distances and shallower depths can cause waves to propagate faster. Tsunamis can cause extremely strong waves, which can endanger divers and affect their ability to move through the water.
3.	**WIND**	Strong winds can contribute to wave heights and intensify wave impacts. However, in the Black Sea, winds associated with tsunamis are not considered a major factor because tsunamis are generated by underwater earthquakes. Reduces the MOB manoeuvrability of the vessel and may result in inability to use the diving boat, delay/failure to rescue tsunami victims.
4.	**CURRENTS**	Remove survivors and a larger search sector is created. There are rising currents, difficult navigation for divers and health hazards for divers and survivors.
5.	**FLOODING**	A tsunami can cause severe flooding in coastal areas. These floods can affect dry land, causing major damage to coastal communities and infrastructure.

4. MATHEMATICAL MODELLING OF TSUNAMI WAVES

The mathematical model approached for tsunami wave modeling was approached by: generation, propagation and inundation. The third and most difficult phase of tsunami wave dynamics deals with the breaking of tsunami waves as they approach the shore.

Estimation of tsunami damage can be done by analysing the results of the mathematical model. The objective is to mention the basics of tsunami mathematical modelling and to highlight the general aspects of it.

To begin, is considered the process of extreme wave generation. Different existing approaches to general mathematical modelling are examined, and then some alternatives are proposed.

Subsequently, it is found that the Boussinesq equations are often the most commonly used to model tsunami propagation and tsunami inundation. The importance, nature and inclusion of effects in long-wave models of tsunami waves are discussed in detail [5].

4.1. Tsunami propagation

This phase depends very much on the lower bathymetry and coastline. The break can be progressive. Then, the inundation process is slow and may take several minutes. The mathematical modeling of tsunami wave propagation is a critical area of study for understanding and predicting the behavior of tsunami.

The break may be explosive and lead to the formation of a plunging jet. The impact on the coast is very rapid [5].

Is discussed the description of the common mathematical model used to study water waves. Horizontal coordinates are denoted by x and y, and vertical coordinates by z [6].

The horizontal gradient is noted:

$$\nabla := \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right) \tag{2}$$

Horizontal velocity is noted:

$$u(x, y, z, t) = (u, v) \tag{3}$$

$$w = (x, y, z, t) \tag{4}$$

The vertical velocity is noted :

The three-dimensional flow of an incompressible inviscid liquid is governed by conservation of mass:

$$\nabla \cdot u + \frac{\partial w}{\partial z} = 0 \tag{5}$$

and conservation of momentum:

$$\rho \frac{Du}{Dt} = -\nabla p, \rho \frac{Dw}{Dt} = -\rho g - \frac{\partial p}{\partial z} \tag{6}$$

$\frac{Df}{Dt}$ is the derivative defined as :

$$\frac{Df}{Dt} := \frac{\vartheta f}{\vartheta t} + \vec{u} \cdot \nabla f, \vec{u} = (u, w) = (u, v, w) \tag{7}$$

Equation (6) becomes:

$$\nabla^2 \emptyset + \frac{\emptyset \partial^2}{\partial z^2} = 0 \tag{8}$$

The momentum conservation equation (3.7) can be integrated into Bernoulli's equation, valid in any part of the fluid. The constant p_0 is a reference pressure (e.g. atmospheric pressure):

$$\frac{\partial \emptyset}{\partial \mathrm{t}} + \frac{1}{2}|\nabla \emptyset|^2 + \frac{1}{2}\left(\frac{\partial \emptyset}{\partial \mathrm{z}}\right)^2 + \mathrm{gz} + \frac{\mathrm{p} - \mathrm{p}_0}{\rho} = 0 \tag{9}$$

4.2. Classical formulation

The surface wave problem consists of solving Laplace's equation in a domain $\Omega(t)$ bounded above by a free moving surface (the interface between air and water) and below by a fixed solid boundary. The free surface is represented by:

$$F(x, y, z, t) := \eta(x, y, t) - z = 0 \tag{10}$$

The shape of the bottom is given by:

$$z = -h(x, y) \tag{11}$$

We consider the free surface as part of the solution. Two boundary conditions are necessary: the first one is declared as kinematic state: $DF\ /\ Dt\ =\ 0$ (the material derivative of F vanishes), which leads to:

$$\eta t\ +\ \nabla_{\emptyset}\ \cdot\ \nabla\eta\ -\ \varphi z\ =\ 0\ la\ z\ =\ \eta(x,y,t) \qquad (12)$$

The second boundary condition is that the normal voltage is in equilibrium at the free surface. The normal pressure exerted on the free surface is given by the pressure difference. Bernoulli's equation is evaluated on the free surface :

$$\emptyset_t\ +\frac{1}{2}|\nabla\emptyset|^2+\frac{1}{2}\emptyset_z^2+g\eta=0,\ \ z=\eta(x,y,t) \qquad (13)$$

Finally, the lower boundary condition is:

$$\nabla\varphi\ \cdot\ \nabla h\ +\ \varphi z\ =\ 0 \qquad (14)$$

$$z\ =\ -h(x,y) \qquad (15)$$

4.3. Surface equations

When β has a small value, the water is not considered deep. The linearized theory of water waves is recovered by letting φ tend to 0. For shallow water wave theory, β is assumed to be small and φ is expanded with respect to β:

$$\emptyset\ =\ \emptyset_0\ +\ \beta\varphi_1\ +\beta^2\varphi_2\ +\cdots \qquad (16)$$

To simplify the calculation, it will be assumed that the water depth is constant
($h\ =\ 1$). Solving Laplace's equation and considering the lower kinematic state gives the following expressions for $\emptyset_1$ and $\emptyset_2$:

$$\emptyset_1(x,y,z,t)=\ -\frac{1}{2}(1+z)^2\left(u_x+v_y\right) \qquad (17)$$

$$\emptyset_2(x,y,z,t)=\frac{1}{24}(1+z)^4\left[(\nabla^2u)x+(\nabla^2v)_y\right] \qquad (18)$$

The 3 equations contain various shallow-water models.

$$ut\ +\ \alpha(uux\ +\ vvx)+\ \eta x\ -\ \frac{1}{2}\beta(utxx\ +\ vtxy)=\ 0 \qquad (19)$$

$$vt\ +\ \alpha(uuy\ +\ vvy)+\ \eta y\ -\ \frac{1}{2}\beta(utxy\ +\ vtyy)=\ 0 \qquad (20)$$

$$\eta t\ +\ [u(1\ +\ \alpha\eta)]x\ +\ [v(1\ +\ \alpha\eta)]y\ =\ \frac{1}{6}\beta[(\nabla^2u)x\ +\ (\nabla^2v)y] \qquad (21)$$

4.4. Classical Boussinesq equations

The classical Boussinesq equations are obtained by replacing u by the depth-averaged velocity, thus:

$$\frac{1}{h}\int_{-h}^{n}u\,dz \qquad (22)$$

$$u_t+uu_x+g\eta_x-\frac{1}{3}h^2u_{txx}=\ 0 \qquad (23)$$

We read:

$$u_t+uu_x+g\eta_x-\frac{1}{3}h^2u_{txx}=0 \qquad (24)$$

$$\eta_t+[u(h+\eta)]=0 \qquad (25)$$

4.5. The energy of a tsunami

Earthquake energy is measured by the strain energy released by the fault. Tsunami energy is estimated to be $4.2 \times 1015 J$.

$$E = \frac{1}{\sqrt{3}} \alpha^{\frac{3}{2}} \rho d^2 (c_0^2 + gd) \int_{-\infty}^{\infty} sech^4 x dx + O(\alpha^2) \tag{26}$$

4.6. Tsunami flooding

The final phase of a tsunami is inundation [7]. Although in some cases it may be important to consider the coupling between fluid and structures, we limit ourselves to describing the fluid flow. The basis of their analysis is the one-dimensional counterpart of the system. In addition, the depth is assumed to be of uniform slope:

$$h = -x \tan \theta \tag{27}$$

Enter the following dimensionless quantities, noting ℓ- the characteristic length:

$$x = \ell \bar{x}, \quad \eta = \ell \bar{\eta}, \; u = \sqrt{gl}\, \bar{u}, \quad t = \sqrt{l/g}\bar{t}, \; c^2 = \frac{h + \eta}{\ell} \tag{28}$$

$$u_t + uux + \eta_x = 0 \tag{29}$$

$$\eta_t + [u(-xtan\theta + \eta)] = 0 \tag{30}$$

Then one can rewrite the hyperbolic equations with respect to the new variables λ and σ defined as follows:

$$\frac{\lambda}{2} = \frac{1}{2}(r + s) = u + t \tan \theta \tag{31}$$

$$\frac{\sigma}{4} = \frac{1}{4}(r - s) = c \tag{32}$$

It gets:

$$x_s - \left[\frac{1}{4}(3r + s) - t \tan \theta\right] t_s = 0 \tag{33}$$

$$x_r - \left[\frac{1}{4}(r + 3s) - t \tan \theta\right] t_r = 0 \tag{34}$$

The following equation is obtained after integration:

$$(\sigma \varphi \sigma)\sigma - \sigma \varphi \lambda \lambda = 0 \tag{35}$$

Two major simplifications have been achieved. The nonlinear set of equations has been reduced to a linear equation, and the free boundary is now the fixed line $\sigma = 0$in the (σ, λ) plane. The free boundary is the instantaneous shore $c = 0$, which finds motion proportional to the rise of a wave on the beach.

5. MAPS MADE IN QGIS SOFTWARE DURING A TSUNAMI IN THE BLACK SEA

Using QGIS software, (fig. 5.1.) were produced maps showing the military operations affected by a tsunami in the Black Sea. These show the coastal inundation of the areas of Babadag, Capu Midia, Constanței and Mangaliei and the effect on military operations carried out by the Naval Forces. The terrain model from which the maps and elevation data were extracted is the Shuttle Radar Topography Mission (SRTM).

Using the QGIS interface and numbering the units as shown in Figure 5.1., it can be seen that the Babadag unit would not be affected by the occurrence of a tsunami in the Black Sea, and that those considered affected would be Capu Midia, Constanta - which includes ships at harbour and divers' activity - and Mangalia. Hydrographic operations and vessels at anchor in the Black Sea would be affected.

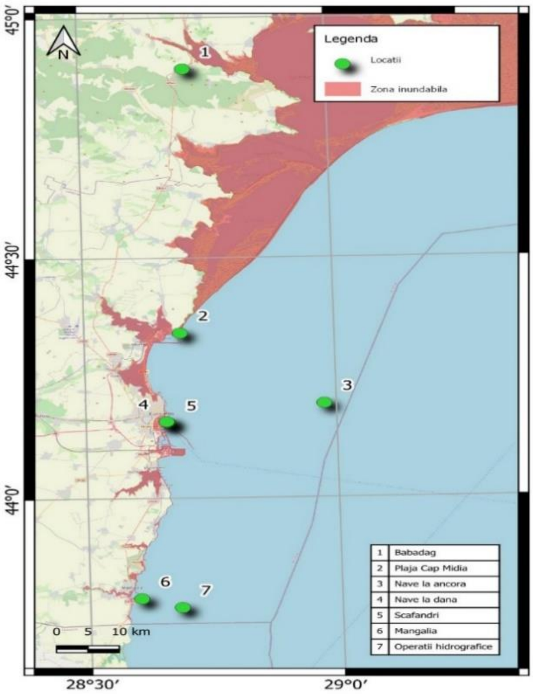

Figura 5.1. : Layout of the affected areas in the event of a tsunami in the Black Sea, including military operations carried out by Naval Forces units in different areas of Dobrogea [8].

Using the QGIS program, it was possible to produce maps including waves of 2, 3, 4 and 5 metres when a tsunami occurs in the Black Sea.

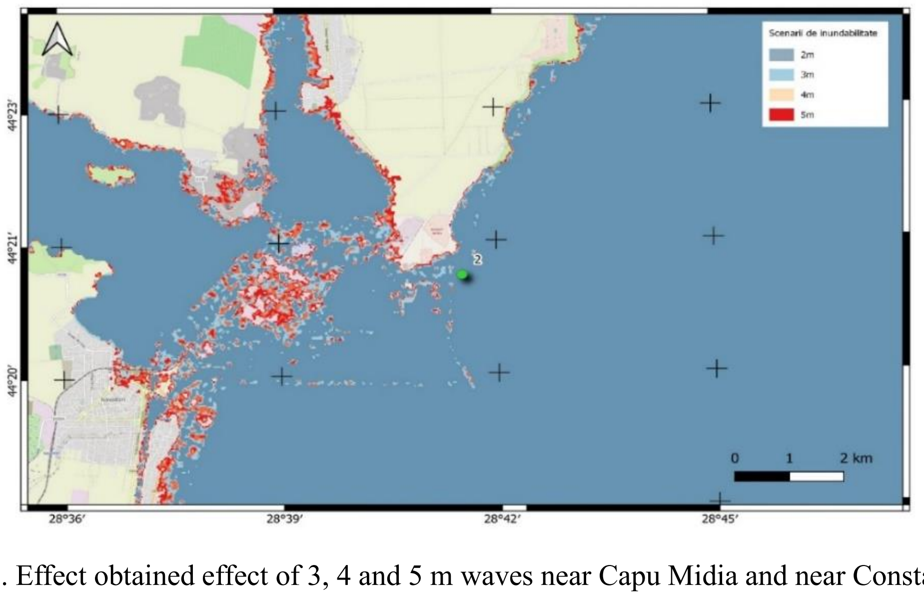

Figure 5.2. Effect obtained effect of 3, 4 and 5 m waves near Capu Midia and near Constanța [8].

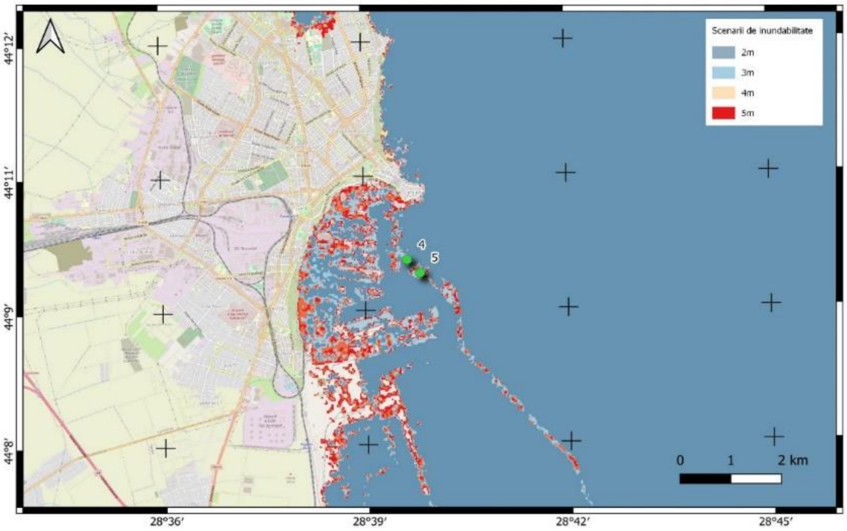

Figure 5.3. Effect obtained of 3, 4 and 5 meter waves affecting the military port of Constanta [8].

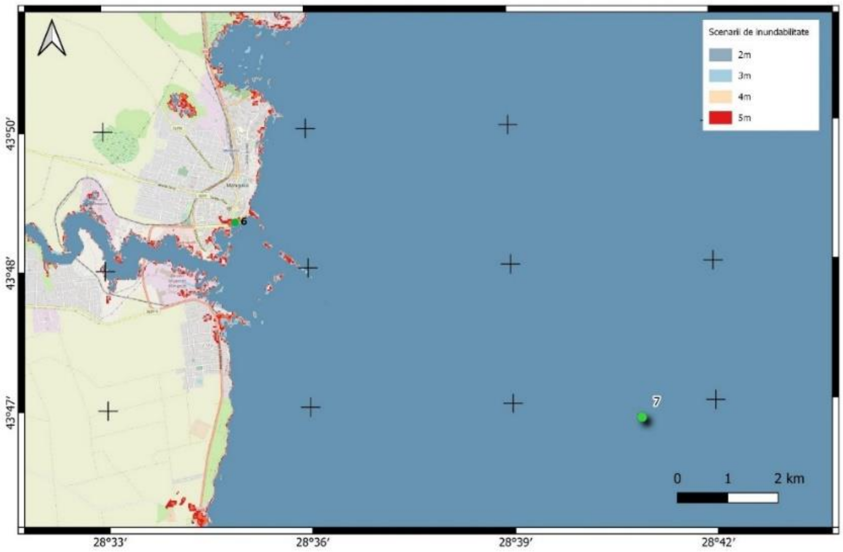

Figure 5.4. Military operations deployed in Mangalia affected by 4 and 5 metre waves when a tsunami occurs, offshore hydrographic operations affected by tsunami occurrence [8].

Consider a scenario in which a seismic event, such as an underwater earthquake or a submarine landslide, occurs off the coast of the southern Black Sea, generating a tsunami with the potential to impact coastal communities. The hypothetical event involves a magnitude earthquake striking the seabed near a tectonically active fault line, leading to the displacement of water and the formation of a tsunami wave.

Impacts:

Coastal Communities: The tsunami wave, upon reaching the coastline, may inundate low-lying areas, causing significant damage to infrastructure, residential properties, and coastal ecosystems. [9] Population centers along the southern Black Sea coast, including cities like Batumi (Georgia), Trabzon (Turkey), and Sochi (Russia), could face the brunt of the impact, resulting in loss of life and displacement of populations [11].

Economy: The economic ramifications of a tsunami event in the Black Sea could be substantial, affecting maritime trade, tourism, fisheries, and coastal industries. Damage to ports, marinas, and coastal infrastructure could disrupt commercial activities and trade routes, leading to long-term economic repercussions for the region.

Environment: Tsunami-induced flooding may result in the erosion of coastal habitats, destruction of marine ecosystems, and contamination of water bodies due to the influx of debris and pollutants. The ecological balance of the Black Sea could be disrupted, impacting marine biodiversity and fisheries resources. [10]

Mitigation Strategies:

Early Warning Systems: Implementing a robust tsunami warning system that utilizes seismic monitoring, oceanographic sensors, and real-time data analysis can provide advance notice to coastal communities, enabling timely evacuation and emergency response.

Land Use Planning: Enforcing zoning regulations and land-use planning measures to restrict development in high-risk coastal areas can mitigate the potential impacts of tsunamis, reducing exposure to hazards and safeguarding vulnerable populations.

Public Awareness and Education: Raising awareness among residents, businesses, and tourists about tsunami risks and preparedness measures through educational campaigns, drills, and community outreach initiatives can enhance resilience and response capabilities.

Creating maps during a tsunami event involves several critical steps, including real-time data acquisition, analysis, and visualization. Using QGIS software, can be generated different type of maps: tsunami inundation maps (show the areas expected to be flooded by tsunami waves that highlights the extent of water penetration into coastal areas and represent an important parameter for evacuation planning and risk assessment), evacuation route map (present the safety evacuation route), real-time tsunami wave propagation map (present a dynamic map for real-time propagation of tsunami waves across Black Sea costal region), damage assessment map (present the damage caused by the tsunami) and risk area map (should present different risk zones depends on elevation, proximity or population density).

Conclusion: While the likelihood of a tsunami occurrence in the southern part of the Black Sea coast remains relatively low, it is essential to recognize and address the potential risks associated with such events. By understanding the geological, oceanographic, and socio-economic factors influencing tsunami hazards, stakeholders can develop proactive mitigation strategies to minimize the impacts and enhance the resilience of coastal communities in the region. Also, development and refinement of numerical models to simulate tsunami wave propagation, inundation, and impact. These models incorporate advanced hydrodynamic equations and real-time data assimilation. A very important, is represented by detailed mapping of coastal topography and bathymetry in order to identify the vulnerable areas. Ongoing research, collaboration, and preparedness efforts are crucial for effectively managing tsunami risks in the Black Sea basin.

References

[1] Vilibić, I., Denamiel, C., Zemunik, P. *et al.,* The Mediterranean and Black Sea meteotsunamis: an overview . *Nat Hazards* 106, 1223–1267, 2021.

[2] Y. Altinok, Tsunamis along the coasts of the Black Sea, *Second Balkan Geophysical Congress and Exhibition, Istanbul, Proceedings of the Conference,* pp. 46-47, 1999.

[3] Aydın, B., Tsunami hazard assessment in the Black Sea., *Journal of Marine Systems*, 117-118, 2013.

[4] D. N. a. I. P. S. Hadi, Integrating computer vision technique to support Tsunami Early Warning System, *2012 International Conference on Systems and Informatics (ICSAI2012), Yantai, China,* pp. 951-1955, 2012.

[5] Y. D. a. Y. Bandung, Analysis of Numerical Model Result To Estimate Tsunami Damage Based

On Inundation Data, *2019 International Symposium on Electronics and Smart Devices (ISESD), Badung, Indonesia,* pp. 1-6, 2019.

[6] Regina, M.Y., Mohamed, E.S. Modeling study of tsunami wave propagation. *Int. J. Environ. Sci. Technol.* **20**, 10491–10506, 2023.

[7] A. a. S. T. Varsoliwala, Mathematical modeling of tsunami wave propagation at mid ocean and its amplification and run-up on shore, *Journal of Ocean Engineering and Science, 6(4),* pp. 367-375, 2021.

[8] 13 06 2023. [Interactiv]. Available: https://www.qgis.org/en/site/about/index.html.

[9] Yasmin, Mariam et al. Modeling study of tsunami wave propagation. *International Journal of Environmental Science and Technology* 20 (2022): 10491-10506.

[10] Vilibić, I., Rabinovich, A.B. & Anderson, E.J. Special issue on the global perspective on meteotsunami science: editorial. *Nat Hazards* **106**, 1087–1104, 2021.

[11] Baranova, E. A., & Kh, M. R. Tsunami Hazard for the Crimean Coast of the Black Sea and the Kerch Strait at the Catastrophic Tsunamigenic Earthquakes, the Locations of which are Close to that of the Historical Yalta Earthquake on September 12, 1927. *Physical Oceanography*, 27(2), 110-125, 2020.