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Tsunami Research In Bulgaria - Gaps, Challenges, And Future Research Directions

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Abstract: *Tsunamis are a severe hazard that results in many deaths and damage to infrastructure, especially along the coasts of tsunami-prone areas along the World Ocean coast. The Black Sea is an inland sea surrounded and intersected by many active faults and geodynamic features that can generate tsunamis.*
Tsunami events are rare in this sea basin, although evidence of such events is described in historical chronicles and recorded over the past century through continuous sea level observations with tide gauges constructed along its coast. We present findings from a synthesis of the studies from the last four decades on tsunamis along the Bulgarian Black Sea coast with broader implications for natural disaster risk management. The overview defines the available gaps and shortcomings in providing necessary input data to model and simulate such events caused by various sources. We highlight the key issues to be addressed and provide some recommendations for the prospects of tsunami research in the Black Sea, focusing on the sustainable maintenance and management of an early warning system for natural hazards in the coastal zone.
Key Word*: Natural hazards, Tsunami, Coastal zone, Black Sea, Research Infrastructure*

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I. Introduction

In recent decades, in line with the global trend of expanding natural hazard research and disaster risk reduction, the hazard and risk assessment of tsunami waves along the World Ocean coast has become a topical research topic. Tsunami research includes the study of tsunami documentary evidence, historical data collection, field experiments, laboratory research, theoretical numerical and analytical modeling, and in-depth analysis of recent tsunami events [13]. Systematic and comprehensive research, theoretical, and model simulations of tsunami waves have begun following the numerous human casualties and devastating damage following several consecutive events over the past two decades. The first event occurred after a powerful underwater earthquake off the Indonesian island of Sumatra on December 26, 2004. The next disaster resulted from an earthquake off northeastern Japan on March 11, 2011, which caused widespread devastation in many coastal areas. The tsunami caused a major nuclear accident at a coastal power plant with long-lasting effects to this day. A similar destructive event occurred on December 22, 2018, as a result of an underwater landslide following the volcanic eruption of Anak Krakatau in Indonesia's Sunda Strait between the islands of Java and Sumatra. The last significant tsunami event was on January 15, 2022, due to the eruption of the Hunga Tonga-Hunga Haʻapai submarine volcano. Volcanic eruptions produce two types of tsunamis: "classic" tsunamis, caused by the displacement of large volumes of water, and meteotsunamis, caused by rapidly developing pressure disturbances in the atmosphere. Its consequences are significant material destruction, more than 1,500 people displaced, and dozens of human victims.

The Black Sea is an inland sea surrounded and intersected by many active faults and geodynamic features that can generate tsunamis. Until three decades ago, the existence of a tsunami threat for this region of the Mediterranean basin was ignored until a document mentioning alleged tsunami events was described by ancient chroniclers [5,6,12]. As a result, within the framework of the European GITEC-TWO project (1996-1998), some tsunami research in the Black Sea region was initiated on an enthusiastic basis by Bulgarian researchers [14].

After that, the extended research about this phenomenon started in Bulgaria. Due to the broad international cooperation, Bulgaria was elected as a member of the Tsunami Commission of the IUGG. Several international, bi-lateral, and Bulgarian research projects related to tsunami research were realized, such as TRANSFER (2006-2009), SCHEMA FP6 EC (2007-2010), MARINEGEOHAZARDS (2010-2013) and CABARET (2016-2019). New emerging specialists from the Black Sea surrounding countries and abroad in the tsunami field started to study tsunamis in the Black Sea (see, e.g., Russia [4,9], Turkey [1,20,23], Romania [10], Greece [13,14], Italy [5,6,20]. Research topics include initial identification, characterization, and mapping of tsunami sources and analysis of the historical tsunami events and their source based on the available historical and contemporary data and evidence. Explorations continued with the analysis of extreme hydro-meteorological phenomena resulting in so-called meteotsunamis [22], tsunami modeling and simulations using different scenarios and input data [2,3,7], identification of earthquake sources of tsunami generation [3,9,13], study of the activity and geometry of tsunamigenic faults in the Black Sea basin [10]. The creation of a tsunami early warning system (TEWS) for the western Black Sea coast was initiated [10,19]. Despite the achievements of research carried out so far on tsunami events in the Black Sea basin, there are still unexplained mechanisms of earthquake generation, unclear geodynamics, and unexplored potentially active faults, as well as easy access to modern high-precision observations from collocated stations equipped with sensors to measure various parameters to provide real-time data for modern research purposes [15].

This work aims to synthesize the studies from the last four decades on tsunamis along the Bulgarian Black Sea coast, complementing a previous review of the scientific results achieved so far [15]. The review defines the available gaps and shortcomings in providing necessary input data for modeling and simulating tsunami events caused by various sources. Based on the analysis, we provide some recommendations for the prospects of tsunami research in the region, focusing on the sustainable maintenance and management of research infrastructural networks for natural hazards in the coastal zone.

II. A research synthesis of main developments and achievements

Literature review

A relatively complete list of tsunamis studies in the Black Sea and surroundings is available on the following link: Tsunamis in the Black Sea | Semantic Scholar. Research publications from the analysis of historical tsunamis show the sources that have caused tsunamis are mainly offshore and close to the coastal line earthquakes (more than 80 %), submarine landslides (10-15 %), extreme hydro-meteorological situations (5-10 %), without credible evidence of other tsunami sources. Scientific research has been aimed at determining tsunamigenic sources, modeling and simulating past events, including those recorded by continuous sea level observations along the Black Sea coast, assessing spatial extent, temporal and spatial resolution, building and maintaining a modern scientific infrastructure, early warning systems, raising awareness of potential hazards from such events along the coast. Results from these studies are published in scientific journals, mainly after the end of the 1970s, when the number grew progressively. For example, for the period 1980-2000, they were about 16; for the period 2001-2010, they were ~18; for 2011-2020 - ~40; and after 2020, about 15.

For the Black Sea basin, tsunami waves are described in historical documents and recorded instrumentally, mainly caused by earthquakes and a small part - by landslides or of meteorological origin [1,4,9,21]. In the updated tsunami catalogs [8], 50 cases have been identified in the Black Sea for the last three millennia [9], and model studies have been performed for some of them [2,3,21,23]. Information about the Black Sea tsunamis of the past indicates that they were observed in separate sections of the coast, some of which were destructive with a wave height of over 2m. They were mainly caused by earthquakes, with epicenters in the sea and a more minor part - on land.

The geodynamic setting determines the conditions for earthquakes, which are most often on the borders of the Black Sea basin and form specific areas of concentration of their epicenters [11,14,19,23]. Such seismic zones are Shabla-Kaliakra, the Crimean Peninsula, three clusters on the Black Sea's eastern shores, and Turkey's southern coast. Of the 29 historical events described according to the new European catalog https://tsunamiarchive.ingv.it/emtc.2.0/, 22 of them are reliably determined [8]. Several scientific publications have presented model studies of tsunami waves induced by other sources in the Black Sea basin (e.g. [2,7,18,21,22]).

Preliminary research on tsunami hazards and risk assessment along the Bulgarian coast has been carried out within the framework of the SCHEMA project [17]. Tsunami modeling was performed by applying a credible worst-case scenario to the Balchik test site along the northern Bulgarian coast. Vulnerability and risk analyses are performed based on Papadopoulos et al.'s [12] chronology and Intensity scale. The probabilistic approach is applied to determine the risk zonation by calculating the simulated inundations of the low-lying areas. Identification of possible underwater landslides offshore are also evaluated after computing the maximum water elevation of the possible induced tsunami based on a selected scenario event. In some places close to the Bulgarian coast, swath bathymetry imaging and high-resolution mapping of marine sediments are still not oriented to tsunami generation studies. A noteworthy atlas for two test sites, Varna and Balchik, has been published [17]. Examples of the maps of vulnerable facilities according to two reliable source models (s1 and s2) prepared are given in Figure 1.

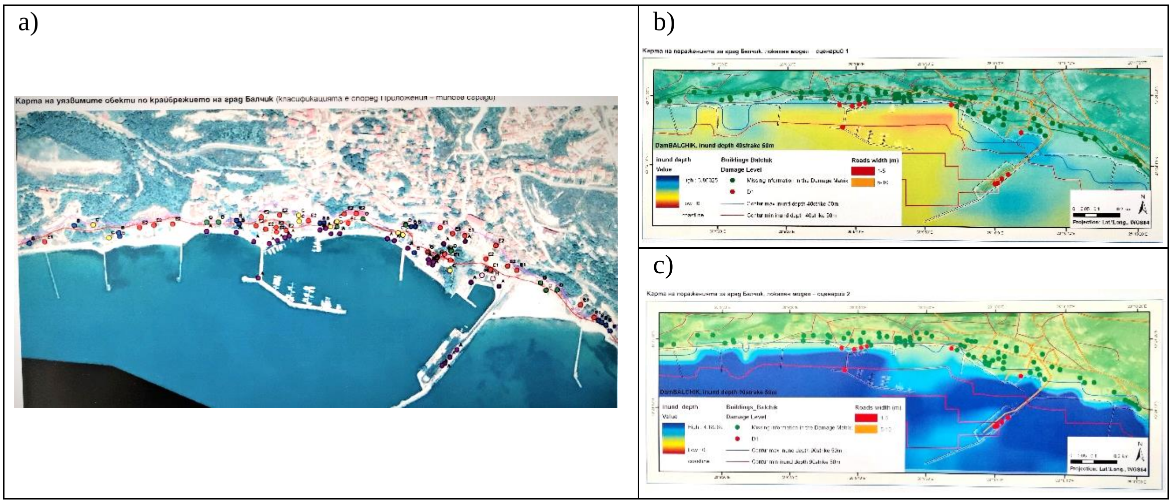

Figure 1. a) Map of the vulnerable facilities caused by the tsunami; Damages in the town of Balchik: b) local source model, s1 and c) local source model, s2 [17]

Development of the research infrastructure

Recently, in the framework of several international and national research projects and following the recommendations of European directives such as the Flood Directive (2007/60/E.C.) and Maritime Spatial Planning Directive (2014/89/E.U.), funds were invested in the modernization and construction of a new research infrastructure along the Bulgarian Black Sea coast. Several digital tide gauges with radar sensors were installed in Balchik, Varna, Shkorpilovtsi, Pomorie, and Burgas, registering 1-minute sea-level variations. The five stations equipped are included in the international networks of EMODNet (European Marine Observation and Data Network, https://emodnet.ec.europa.eu/), CMEMS (Copernicus Monitoring Environment Marine Service, https://marine.copernicus.eu/) and GESLA (Global Extreme Sea Level Analysis, https://gesla787883612.wordpress.com/), as hourly values of the Black Sea level are provided by the Institute of Oceanology at the Bulgarian Academy of Sciences (IO-BAS). Unfortunately, some are inactive for different reasons and do not provide real-time data.

In the equatorial waters, several buoys were placed near the coast for monitoring extreme meteorological, seismic, and tsunami events in real-time, which portals are shown in Figure 2. The marine meteorological network of the National Institute of Meteorology and Hydrology (NIMH) consists of 7 buoys, and the second network is managed by the IO-BAS. The IO-BAS portal displays data from some of the buoys maintained by the NIMH.

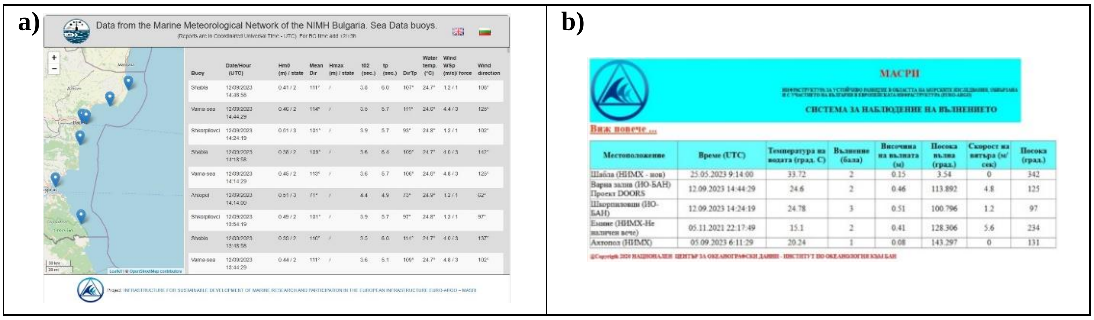

Figure 2. a) Marine Meteorological Network of buoys maintained by the NIMH Bulgaria (http://mm.meteo-varna.net/?lang=Eng); b) Marine observational system of the IO-BAS (http://bgodc.io-bas.bg/sofar-buoys/)

A synthesis of main achievements

The main achievements of the tsunami research in Bulgaria can be summarised as:

- Initial identification of seismic sources that can trigger tsunami events with possible threats to the Bulgarian coast.
- Numerical models of tsunami influence (source definition, vulnerable objects, risk profiles) have been presented for selected coastal towns.
- Models of kinematic early warning for marine hazards, including tsunamis in the Black Sea, have been developed (considering travel times, velocities and inundation areas for selected areas of the Bulgarian coast), and a decision matrix with three levels of alert has been developed.

III. Identified research and institutional gaps

Despite efforts to develop and maintain the research infrastructure in the Bulgarian coastal zone, several research gaps can be identified:

- There is a need for significant improvements in research infrastructure, which can be supplemented by the collocated seismological, GNSS, geophysical, and other equipment. A necessary condition to be observed is that there is to avoid a duplication of the installed equipment on the land and offshore.
- Further detailed prospecting is necessary for the tsunamigenic active faults, determination of their parameters, unambiguity determination of the earthquake mechanisms, and assuring high-precision DEM for topography and bathymetry in the coastal zone.
- Necessity to ensure free access to real-time data with the necessary detail and accuracy.

The low efficiency of the tsunami modeling and simulation is due to the input data's limited spatial and temporal accuracy. Among the unsolved scientific tasks is also The incomplete, difficult-to-access and scattered information about past tsunami events due to the different sources of origin on the Bulgarian coast hampered the realistic modeling and simulation of tsunami events. One of the causes is the small number and poorly documented events, which prevent assessment of the danger and risk of tsunamis with low probability. In most cases, the modeling scenarios are based on repeating coastal tsunami wave heights from historical records, which can hardly be judged scientifically. For more comprehensive and detailed studies, spatial data with needed accuracy for 3D modeling (e.g., BIM and GIS integration modeling) are needed.

Some institutional gaps and shortcomings have also been identified, which are expressed in:

- Lack of good coordination, communication and cooperation between the interested parties, including scientific organizations, state institutions, business organizations, insurers, NGOs, and other interested parties.
- There is a lack of publicly available information in Bulgaria about the tsunami risks for the Bulgarian coast.
- Tsunami simulations for the Bulgarian coastal zone are in the initial stage due to some difficulties in providing data with the necessary detail and accuracy, such as active faults, parameters of earthquake mechanisms, and high-precision DEMs. The lack of a sustainably supported scientific research infrastructure of sensor networks for measuring various parameters in the coastal zone significantly complicates the verification of model and simulation studies, for which input data from actual registered extreme events are required.
- The country lacks appropriate legislation to regulate early warning and actions in crises in the event of tsunami events.

IV. Discussion on future perspectives of tsunami research in Bulgaria

The European and national guidelines for assessing the danger and risk of natural hazards along the coast do not contain specific provisions for preparing specialized maps for the threatened low-lying coastal areas. Soon, scientific research can be aimed at completing the information on tsunamis, paleo tsunamis, seismic sources (faults and zones), and description of non-seismic sources (especially landslides in seismic zones) in the Bulgarian coastal zone [15]. Detailed land and bathymetry DEMs of the low-lying coastal areas along the Bulgarian coast are needed for numerical modeling and simulation. Understanding tsunami generation processes has improved significantly in recent years, providing an opportunity for international cooperation and exchange of good practice and experience. The development of real-time monitoring systems of the potential hazards and risks in the coastal zone and their integration into multidisciplinary, international systems for sustainable coastal zone management are needed for sustainable coastal development. In general, at first, improving the accuracy and increasing the resolution of the numerical models of the topography of the land and the seabed used in the modeling and the application of new methodological approaches in the analysis of the geological environment are among the opportunities to improve the scientific results of the research. Designing the data, modeling and simulation process flow, writing technical documentation, and comprehensively testing numerical codes for validating tsunamis due to different triggered sources will contribute to more accurate and realistic modeling of such events. Special attention and study of non-seismic tsunamis such as landslides, asteroid impacts, and meteotsunamis should be devoted. Significant improvement and validation procedures of models are needed to deal with floods in the complex inland environment (e.g., considering buildings, infrastructures, and other assets in the coastal zone). One challenging scientific task is in-depth morphotectonic analysis of active faults in the Western Black Sea Basin. Another direction to work on is filling data gaps collected for past events and documented by sea level registration through tide gauges (TG) along the Bulgarian coast, QA/QC of continuous sea level records covering observed tsunami events in the Black Sea after 1928 to 2012 (from analog paper marigrams) and after 2013 (from digital records). Based on the newly achieved results, the tsunami risk analysis in a multi-hazard dimension should be integrated into coastal zone management. Another national research task can be to explore tsunami forecasting methods with a view to the application of TEWS in the Euro-Mediterranean region. The next aim can be to evaluate the destabilization of the sensitive spots on the coast due to the refraction, coastal and bathymetry influence.

In the long term, research efforts should focus on improving tsunami early detection and warning methods, extending hazard-to-risk analyses to all tsunami-prone coastal areas. As a result of scientific studies, viable countermeasures against tsunami attacks in the coastal zone can be developed by defining building design codes and planting plants on exposed seashores. Internationally and nationally, vulnerability and risk analysis standards can be defined and widely publicized among interested parties, such as designers, marine engineers, and specialists involved in constructing marine infrastructure. Education and training for preventing the consequences of natural hazards for Bulgarian coastal communities, including tsunamis, is of essential importance. An important element in raising awareness is the development of web-based emergency management and early warning systems that are easily accessible through mainstream Internet communication systems. Through such systems, effective preparedness is maintained to deal with and reduce the negative consequences of natural disasters in coastal areas potentially threatened by natural disasters.

V. Conclusion

Adequate scientific knowledge is needed to effectively anticipate the danger of a tsunami and raise public awareness, reducing the vulnerability and impact of such phenomena on potentially endangered areas along the low-laying coastal zone.

In recent years, innovative and tested approaches for tsunami early warning and risk reduction have been developed based on advanced research-based sensor networks that operate in disaster-damaged environments. Tsunami events are rare, but when near populated coastal regions, the damage and loss of life can be enormous. Scientific advances contribute to creating systems that can warn coastal communities in time to reduce the negative consequences of coastal disasters. The development of information and communication technologies and advanced computing methods, including artificially intelligent methods, make it possible to process large volumes of data that are used in modeling and simulating tsunami events and their verification with actual events.

Interdisciplinary collaboration between scientists from different geoscience disciplines is a prerequisite for providing scientific evidence for sustainable marine spatial planning. The application of advanced multidisciplinary methods could improve the elucidation of potential tsunami hazards along the Bulgarian coastal zone. Investigating the natural hazards, vulnerability, exposure, and risk is necessary to improve the risk management of the eventually flooded coastal areas.

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