Coastal Environmental Impact of Geohazards in the Area of the Habibas Islands (Western Algeria, Alboran): Insights from GIS-Analysis and Remote Sensing

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ABSTRACT

Algerian coastal areas in the southern part of the western Mediterranean Sea are prone to geohazards such as tsunami waves, storm surges, earthquakes, submarine mass movements, and volcanism. Located in the Gulf of Oran, the Habibas Archipelago is a well-preserved bio-environment where fauna and flora are unique. This region is nevertheless a zone where marine traffic (oil) and oil ports pose a threat to environmental offshore pollution. This study is focused on submarine mass movements and their potential to cause local tsunami waves. Digital Elevation Model (DEM) data and the DEM-derived morphometric maps support these investigations being integrated into a GeoInformation System (GIS). Bathymetric data of the western Mediterranean Sea are used to derive causal factors that influence the susceptibility to submarine mass movements. Sentinel 2, Landsat 8, and Sentinel 1 radar images help to identify coastal areas prone to landslides and the coast-near structural pattern. By integrating data collected from the literature and maps (geology, tectonics, earthquakes, mass movements) into a GeoInformationSystem (GIS) and by using remote sensing analysis, it might be possible to derive more precisely in the case of submarine landslides and turbidity currents in the which direction potential tsunami waves caused by these mass movements might be focused and directed.

Keywords: Earthquakes, GIS, Habibas, Remote Sensing, Submarine Mass Movement, Tsunami, Western Mediterranean.

I. INTRODUCTION

Natural disasters generated by submarine processes such as submarine mass movements, tsunamis or volcanic eruptions in the Mediterranean are documented in historic records and recent measurements. There is a noticeable correlation between known slope failure events and available high-resolution bathymetric and geophysical data. This correlation stresses that, despite recent advances, the catalog of submarine slope failures in the Mediterranean is still incomplete (especially for the North African margin) and further efforts need to be undertaken in order to address this situation [1]. The same can be stated for the potential of mass movements to cause tsunami waves. Tsunami generation is dependent on several factors, including seismogenic faulting, volcanic activity, landslide processes, and offshore sedimentation. In the Western Mediterranean Sea, most failures have limited volume, and short runout and originate in relatively deep water. Therefore, only the largest albeit infrequent events are likely to trigger larger tsunami waves. Seismicity is a major controlling factor in the distribution, magnitude, and typology of submarine landslides [1], [2], but other factors, mainly fluvial sediment input and margin progradation [3], [4], come to play an important role, too [5].

Located in the western Mediterranean, west of Oran, the Habibas archipelago (Fig. 1) is a bio-rich area that is part of the Specially Protected Areas of Mediterranean Importance (SPAMI’s list) since 2005 [6]. In addition, since 2005, an NGO program called the Mediterranean Small Island Initiative (PIM) [7] set up several actions for managing this classified nature reserve and worked to draw up an inventory of the marine and terrestrial species of the islands. This region abounds in Mediterranean seabirds and for many, the archipelago is a critical habitat where to reproduce.

The Alboran and the Algero-Provinal basin are locations for earthquake-triggered and landslide-triggered tsunamis (Fig. 1) [8]. Several authors documented that in October 1790, a destructive earthquake hit the Spanish and the Algerian coasts [9]-[12]. While the historical documents reported the intensity of the mainshock could be IX (MSK) [9], other studies attempted to reevaluate the magnitude of the earthquake considering a well-documented list of European and Algerian sources and suggested an intensity of VIII (EMS) [10]-[12]. The epicenter is supposed to be located offshore Oran [10]. Consequently, to this earthquake, sea waves were reported in the coastal Mediterranean [9]. Nevertheless, because of the revision of the magnitude of this earthquake, the triggered tsunami reported in [9] revived the debate about tsunami hazards in North-Western Algeria [10], [11].

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To this matter, only interdisciplinary research could approach the combined geological and geophysical factors resulting in assessing the potential for marine geohazards. In this regard, it is then quite notable to integrate into the debate the evolution of the shoreline with time in the Oran – Arzew region [11]. Moreover, several cases of mass movements comprising different types of slope failure such as block gliding or turbidity currents have been identified in the Alboran Sea suggesting new combined scenarios (earthquakes and landslides sources) for local tsunami occurrence and re-assessment of the potential of coastal flooding [13]–[15]. In January–March 2016, a seismic sequence with a mainshock of magnitude Mw = 6.3 struck the southwestern Alboran [16]. While this earthquake mostly originated from normal and strike-slip faulting [16], today we know that not only strike-slip can contribute to generating sea waves [17] but also, they may trigger submarine mass movements and, thus, generate potential local tsunamis. Hence, in this work, we aimed at re-examining potential sources for tsunami hazards as recommended by [8] to survey for slope failure.

Marine geohazards in the Alboran is of primary concern for environmental purpose as the offshore industrial traffic developed considerably between North Africa and Europe (Fig. 1). Impact of sea slides, storm surge, and sea waves (earthquake and slides sources) on pipelines, tankers, and vessels are of concern when it comes to preserving water quality from marine contaminants, toxic substances, and pollution. Moreover, Oran and Arzew are oil export ports with coastal terminals. A first attempt to highlight this issue for Arzew bay presented the environmental risk for the Arzew wetland when exposed to triggered sea waves [24].

The tsunamigenic potential of mass movements greatly depends on the water depth, the submarine geomorphologic conditions, and the size and mechanisms of the slope failure, even if the initial acceleration and velocity play a significant role [25]. The goal of this study is to contribute to the detection of morphometric properties of the sea bottom topography that might lead to a higher susceptibility to mass movements by using bathymetric data. Further on, the controlling factors have to be investigated such as the understanding of pre-conditioning factors in different tectonic and sedimentary environments, the identification of controlling factors on slide kinematics and movements, the understanding of the transfer of energy from submarine landslides into tsunami waves and quantifying hazard from submarine landslides and related tsunamis. Submarine landslides occur on tectonically dominated margins as well as on passive margins and volcanic island flanks of Mediterranean margins. However, tectonically quiet zones seem to have the highest density of known large events. This observation stresses that the balance between pre-conditioning and triggering factors needs to be correctly assessed [2].

In this paper, we present a compilation of sources for geohazards in the Alboran and Algero-Provençal basin from an analysis of the open-source available data (published papers, website, remote sensing images) using ArcGIS 10.8.2 and QGIS software package.

**II. DOCUMENTING ON THE WESTERN MEDITERRANEAN: COMPILING DATA (LITERATURE)**

The Mediterranean is a geologically complex area with a large diversity of geological environments: back-arc extensions, incipient continental collision, active and passive margins, transcurrent margins, large river deltas, sediment-starved margins, and volcanic islands. More than 50 % of all landslides in the Mediterranean Sea originate on the continental slope [1]. Furthermore, the presence of a thick,
widespread salt body in the relatively shallow subsurface has profound implications for fluid flow and tectonics of the continental margins [2].

Tsunami generation is dependent on several factors, including seismogenic faulting, volcanic activity, landslide processes, and offshore sedimentation. Seismicity is a major control in the distribution, magnitude, and typology of submarine landslides [1], [2], but other factors, mainly fluvial sediment input and margin progradation [3]–[26], come to play an important role, too [5].

Submarine landslides occur on tectonically-dominated margins as well as on passive margins and volcanic island flanks of Mediterranean margins. However, tectonically quiet zones seem to have the highest density of known large events. This observation stresses that the balance between pre-conditioning and triggering factors needs to be correctly assessed [2]. Hence, investigating triggering mechanisms is crucial for understanding the potential source of geohazards (slides, tsunamis). It has been reported and shown that three internal domains characterize mass transport deposits (MTDs) including normal faults in the extensional domain (source area), chaotic structures in the translational domain (evacuation area) and folds and thrusts faults in the contractual domain (depositional area) [25].

Headwall scars of submarine landslides in the Mediterranean Sea may disrupt significant portions of the seafloor and extend to distances larger than 100 km. However, about 75% of all failure scars have lengths not exceeding 10 km [1]. For example, in the tectonically active Calabro-Tyrrhenian margin, small disintegrative-type slides mainly occur in the areas with steeper gradients, such as canyons and tectonically controlled scarps while larger and isolated landslides occur in open slopes [25]. In the Iberian Margin earthquakes are the most likely triggering mechanism for synchronous, widely spaced distributed turbidites during the Holocene when the sea level was relatively stable [28]. The Algerian margin is a tectonically active region driven by the convergence between the African and the European-Eurasia tectonic plates with shallow earthquakes that can be destructive. The seismicity is nevertheless mostly moderate with tremors that have magnitudes that often range between 4 to 5. Fig. 2 shows the active tectonic of the Alboran and the Algero-Provençal basin compiled from [11]–[13]. Quaternary seismites from [29] are also reported and give evidence of past strong earthquakes’ shaking in western Algeria. Not only can tremors displace sediments and debris, but rivers and lakes transport as well sedimentary bodies into source areas for submarine landslides and turbidity currents. A geospatial analysis from Landsat imageries in the Boumerdes region revealed that during the magnitude Mw 6.9 destructive earthquake (May 2003) that triggered a tsunami in the western Mediterranean up to the French and Spanish Coasts (Balearic), submarine mass movements and higher sediment discharge of the rivers into the sea had an influence on the water dynamics [30]. Fig. 3 shows the distribution of the earthquakes recorded by the IGN (Spanish Instituto Geografico Nacional) between March 1900 to January 2022 [31]. The water stream (rivers and lakes) and the geology are as well represented after [32], [33]. Based on a geophysical offshore survey, numerous relatively small-size submarine landslides mainly located on canyon flanks and at the foot of continental slope escarpments of tectonic origin have been imaged and mapped on the continental slope offshore Algeria [34]–[37]. Sediment waves have then been there identified [35]–[37]. Here, Fig. 3 also reports the evidenced mass movements and mass transport deposits from [36] and [2] in northwestern Algeria. Turbidity currents, mass transport deposits, and rivers, discharge was identified from echo types identified in offshore seismic profiles [35]. Sedimentary deposition processes in the region are as well extracted and represented from [35] in Fig. 3.

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Fig. 2. Active tectonics in the western Mediterranean (Alboran and Northwestern Algeria) compiled from [11]–[13]. The bathymetry (topography) is from the GEBCO 15 arcsecond interval grid data sets [19]. The coastline (10 m) is from [20]. The tsunami here reported is from [21]–[23]. The seismites are from [29].
III. DATA AND METHODS

Digital Elevation Model (DEM) data and the DEM-derived morphometric maps integrated into a GeoInformation System (GIS) offer a very useful tool for geohazards analysis.

Sentinel 2 and Landsat (Landsat 8, the Operational Land Image-OLI) optical data were integrated into a GIS database. ENVI software from Harris Geospatial Solutions and the Sentinel Application Platform (SNAP) provided by ESA were used for digital image processing. Sentinel 2, Landsat 8, and Sentinel 1 radar images as well as BingMap of Microsoft and WorldImagery-files of ESRI help to identify coastal areas prone to landslides and the coast-near structural pattern.

Digital Elevation Model (DEM) data gained from the Shuttle Radar Topography Mission (SRTM) and ASTER DEM data, were downloaded from open sources such as USGS / Earth Explorer, and Sentinel data from the Sentinel Hub / ESA.

Bathymetric data of the western Mediterranean Sea are used to derive causal factors influencing the susceptibility to submarine mass movements, such as slope steepness, curvature, orientation, and height drop. The bathymetric data provided by the General Bathymetric Chart of the Oceans (GEBCO), International Hydrographic Organization, and the Intergovernmental Oceanographic Commission of UNESCO were integrated into the research in order to derive morphometric maps such as slope and hillshade maps from the sea bottom and drainage basins from the surrounding areas. European Marine Observation and Data Network (EMODnet) bathymetric data provided by the EMODnet portals as initiated by the European Commission were added to these investigations as well [38].

QGIS (open source) and ArcGIS are particularly suitable packages for geohazards assessment. In this work, the sea bottom topography is examined through the height level, slope, aspect (orientation and direction of the slopes), and the hillshade maps to investigate the likelihood for the western Mediterranean for potential mass movements triggering sea waves.

Critical areas are delineated that have the potential to be prone to mass movements because of their geomorphological properties and disposition. In particular, the criteria for the delineation of potential take-off areas for different types of mass movements are described as follows:

- Head-wall of shelf indenting canyons with characteristic landslide scars;
- Significant height drops;
- Steep slopes along canyons;
- Steep slopes along the shelf and submarine mountains and hill ranges.
IV. RESULTS

A. Mapping of Coastal Areas Susceptible to Slope Failure

Fig. 4 presents the potential of coastline landslides. Only small landslide areas are visible on satellite images (Bing Maps Aerial of Microsoft and the World Imagery file of ESRI).

No larger than 2 km (Fig. 4), slides regularly distributed in the bay of Oran are located within a thrust active faulting context with strike-slip and normal faults (undifferential faults in Fig. 2) where the geology is dominated by dunes, quaternary (alluvium, marine sandstones, ancient beaches), late marine Miocene and lagoon (gypsum shale) and Cretaceous-Jurassic deposits (see Fig. 3). Nearby Mostaganem, these landslides are located in an area marked by thrust, strike-slip and undifferential active faulting where the deposits are dunes, quaternary, Villafranchian (lake limestone, shale with lignite) and marine Oligocene sediments (Fig. 2, Fig. 3 and Fig. 4). The hydrographic network that is present in the coast of Mostaganem is dense in comparison with the bay of Oran (Fig. 3). The highest concentration of visible landslides from the satellite images is between the Beni Saf and Oran (Fig. 4). Marked by the existence of a river network, igneous rocks (andesite and tuff; rhyolites), Quaternary (marine sandstones), marine Miocene (conglomerate, blue marls, sandstones, dunes formations), late/upper marine Miocene and lagoon and upper/late marine Miocene (shale, limestone, sandstone), this region is connected to the thrust active faulting system that characterize north western Algeria and is the closest to the Habibas archipelago (Fig. 2, Fig. 3 and Fig. 4).

Fig. 4. Potential coastal landslides in Western Algeria derived from Satellite images (Bing Maps Aerial of Microsoft and ESRI). Volcanoes from the Holocene and Pleistocene are here as well represented [39].

B. Analysis of Bathymetric Data

The orientation of submarine slopes and the course and direction of larger canyons and channels with potential take-off areas for mass movements play an important role when considering the tsunami hazard of the Algerian coast related to mass movements. Based on GECBO data and through GIS analysis, potential take-off areas have been identified at the head-walls of shelf-indenting canyons and for mass movements along the continental margins with significant height drop in the Alboran and east of the Algero-Provençal basin (Fig. 5).

Slope and aspect maps were analyzed in order to derive which submarine steeper slopes are oriented towards the south and, thus, towards the Algerian coast. Submarine slopes oriented in a southward direction (green and blue colors, Fig. 5a and Fig. 6) and potential locations of take-off areas are shown (black points). Sudden mass movements especially from these slopes oriented towards the south, could create high-energy waves directed to the Algerian coast.

Many of the take-offs are located on slopes oriented southeast (Fig. 5a). The submarine “drainage basins” are as well calculated within the Hydrology tools of ArcGIS which means in this case, assessing information in which submarine basins, valleys, and channels the potential mass movements might be directed. In Fig. 5a and 5b, the valley bottom lines are drawn with blue lines.

Slope angles above 60° are extracted from the slope gradient maps based on GECBO and EMODnet bathymetric data. Steep slopes with more than 60° slope angle are found at the northwestern Algerian margin and in the southern part of the Alboran Sea (Fig. 5).

Fig. 6 shows in detail the distribution and the direction of slope angles along the western Algerian margin with the documented mass movements after compiling data from literature [2], [36]. Several potential take-off sites have been found offshore Oran and east of Mostaganem (Fig. 6). Finally, marine scars were also evidenced along the Algerian Margin where slope angles above 60° were derived from the GECBO data along the Habibas escarpment (Fig. 6).

Many documented mass movements from [2], [36] are clearly located at the foot of the submarine canyons, nearby the slope angles above 60° and below -1000 m height level.

To summarize the causal factors increasing the susceptibility to submarine slope failure and mass movements because of the morphometric disposition such as slope degree > 60 ° or a high curvature, a weighted overlay approach was carried out in ArcGIS (Fig. 7). In the weighted overlay procedure, these selected morphometric factors were summarized, merged with equal percentages of influence and represented in a map, subdividing the resulting map into several classes from 0 to 6. The dark-red areas indicate those areas prone to a higher susceptibility to slope failure due to their morphometric disposition.

The results obtained for the Habibas islands are reported in a separate section hereafter for more clarity.

C. The Oran-Habibas Zone

Fig. 8 shows the slope analysis, the potential take-off sites, and the landslides (satellite images) in the Oran -Habibas region. The Habibas islands are situated at the head of a steep escarpment with a significant height drop of more than 1000 m (Fig. 8a and 8c). The documented data reveals this sector is marked by the coastline and offshore strike-slip, normal and thrust faults (undifferential faults, Fig. 2) with moderate and shallow seismicity. Echo characters typical for turbidity deposits, mass transport deposits, coarse sediments, river discharge, and coastal currents deposits have as well been documented (Fig. 2 and Fig. 3).

While slope angles are between 40° to 45–50° along the coast, they reach values above 60° along the Habibas escarpment (Fig. 8a and 8b) where the height level is between 300 to 2000 meters in depth.
The documented mass movements from [2], [36] are then visible in the deeper part of the sea floor where the slope steepness decreases until the seafloor becomes mostly flat with a height level ranging between 2000 to 2500 meters in depth (Fig. 8a and 8c). The hillshade function there helps to better visualize the morphology of the sea-floor (slope angle and direction) (Fig. 8b). Finally, potential take-off areas have been found east of the Habibas islands, nearby a marine scar that extends between the west and east part of the margin while entering the area where the values of the slopes become higher than 60°.

It becomes evident in Fig. 8a, that the quality of the bathymetric data is varying depending on their availability. The slope gradient map based on EMODnet bathymetric data shows higher resolution and lower resolution segments (circa 115 m). Nevertheless, traces of slope instabilities are visible as arc-shaped, parallel lines.

D. Delineation of Potential Catchment Areas for Mass Movements

Fig. 9 demonstrates the drainage basin calculation and flow accumulation results using the Hydrology tools of ESRI in ArcGIS based on GEBCO data from southwest Spain and the coastal area of Oran. Although these tools are created for land surfaces, they support the morphometric analysis of the sea bottom as well. Of course, the conditions in a submarine environment are different from land surfaces as many additional factors play an important role like water pressure, streaming pattern, sediment content, etc. Nevertheless, these calculations help to get an idea about the size, contour, and shape of submarine catchment areas for mass movements and, thus, about the size of potential mass movements and their flow direction. Each color in Fig. 9 represents a different catchment area for smaller landslides whenever it was triggered. On the land surface, each color comprises the delineation of a drainage basin and morphological watersheds.

Most of the potential take-off areas there represented are connected with the submarine valleys (Fig. 9a and 9b). The documented mass movements from [2], [36] also reported in Fig. 9 are correlated with numerous small catchment areas. Hence, although the resolution of about 450 m of the available bathymetric GEBCO data is low, it is clearly visible that the size and volume of the potential mass movements within the smaller valleys along the steep slopes of the Habibas escarpment in the north of Oran are relatively limited. Only in the case of simultaneously mass movements in the different take-off areas triggered by events like a stronger earthquake or intense aseismic movements due to the northwards drift of the African plate noticeable tsunami wave
could be expected. Even then, the local lithologic and tectonic conditions play an important role.

The morphologic delineation highlights different sources for potential sediment inputs and outputs. Hence, in the northwestern part of Algeria, several distinct geological units that can feed the same area of deposits or deposits may consist of one major lithologic series (Fig. 3, Fig. 9a and 9c).

The 3D perspective view shown in Fig. 9c illustrates the potential catchment areas for coastal mass movements favored by the slope steepness and the identified take-off areas in the gulfs of Oran and Arzew. The seismites evidenced in Mostaganem and the complexity of the active fault system, their displacement type, and moving direction are to be considered for triggering landslide materials following the catchment areas (Fig. 2, Fig. 3, Fig. 9).

In case of larger mass movements along the southward oriented, steep slopes, especially in the northern part of the Algerian Basin and along the Mazarron Escarpment, there might be local tsunami waves affecting the correspondent parts of the Algerian coast. Most of the larger canyons in the western Mediterranean Sea are oriented in the W-E direction. With potential turbidity currents and debris flow directed towards the east, the main tsunami front caused by sudden submarine mass movements might be focused in the eastern direction.

If a stronger earthquake happens along the Mazarron Escarpment (Fig. 9a) in the northern part of the Algerian Basin near Cartagena, it could trigger mass movements. As a consequence, tsunami waves could be created that would affect the Gulfs of Oran and Arzew. A tsunami event in the Mazarron Escarpment area was documented on 13.01.1804 in the NOAA tsunami event list. The input of sediment flow, turbidity currents, or debris flow from the semi-circular oriented, submarine valleys is directed to a joint accumulation and deposit area (Fig. 9a).

Fig. 8. (a) Slope degree map from the Oran – Habibas region based on EMODnet Digital Terrain Model (DTM) data (using ArcGIS 10.8.2), (b) Hillshade map from the Habibas island area indicating its position near the steep Habibas Escarpment with slope degrees > 60° (dark-red) (with ArcGIS 10.8.2). Blue lines derived from flow are tracing the valley bottoms. Landslides visible on high-resolution satellite images are represented in red colors. Identified marine scars (GIS) are mapped as black lines. Documented mass movements from [2], [36] are shown as well, and (c) Height level map based on GEBCO bathymetric data. Blue lines derived from flow are tracing the valley bottoms. Landslides visible on high-resolution satellite images are represented in red colors. Identified marine scars (GIS) are mapped as black lines. Documented mass movements from [2], [36] are shown as well.
E. Streaming Pattern

To observe the coastal streaming patterns, Landsat imageries (RGB images, Bands 2, 10, and 7) were used. They show the color-composite of three spectral bands reflecting the earth’s surface in different spectral segments. Fig. 10a shows the water streaming pattern of the Gulfs of Oran and Arzew on 06.10.2021 revealing currents in the Gulf of Arzew. The interaction of the water streaming pattern and circulation with the coastal morphology is evident. In Fig.10b the same Landsat scene was merged with a GEBCO terrain model data-based hillshade map. The streaming pattern is obviously influenced by the shelf morphology and, of course, by wind directions and intensities at the acquisition time of the image.

Increasing extreme weather events due to climate change combined with flash floods and, thus, higher sediment input in shelf areas will have an influence on slope stabilities, too.
V. Discussion

A. Potential Submarine Mass Movements

The results here presented aim at showing what are the pre-conditioning factors for offshore mass movements in the Alboran and the Algero-Provençal basin.

Causal factors for the susceptibility to submarine mass movements causing tsunami waves are mainly significant height drops, steep slopes, the orientation of slopes, earthquakes, active fault zones, high sediment input, the specific lithologic and structural conditions, and aseismic, continuously movement due to plate tectonic compression.

The calculation of the flow accumulation and of drainage basins based on GEBCO data carried out in ArcGIS using the HydroTools also provides an idea of where mass movements and their potential, approximate size, and volume might be directed within the submarine topography.

Potential take-off sites were evidenced with locations well correlated with marine scars and critical slope characteristics for potential mass movements.

However, the water circulation and streaming pattern, temperature, and salt concentrations have to be considered as well as sediment transport. Here, we found through a morphologic delineation analysis that coastal sediments could feed the submarine valleys offshore. The Landsat streaming pattern helped to provide arguments for coastal waves disturbances as well.

However, the water circulation and streaming pattern, temperature, and salt concentrations have to be considered as well as sediment transport.

Even if submarine landslide morphology and distribution can be controlled by several factors and processes such as lithological characteristics, tectonic activity, sediment supply, pore water overpressure, cyclic load induced by earthquakes or waves, mud volcanoes, flank undercutting due to turbidity currents), it is noteworthy that most of the observed variability seems to be strictly related to different physiographic/morphological domains where the landslide formed [40], [41].

Tectonically controlled scarp and canyon flanks are other important factors regarding the susceptibility to slope failure.

Many traces of slope failure along canyon headwalls are commonly characterized by a cauliflower shape due to an array of small (diameters of tens of meters) and coalescent scars. Whatever their location on the continental slope, many take-off areas for landslides exhibit an ellipsoidal or amphitheater-like morphology [3].

A canyon is considered geomorphologically active when sediment-loaded and erosive gravity currents take their course and settle at the foot of a continental slope [42]. In the Algerian margin, a sector where the continental shelf is narrow or even non-existent, canyons and valleys are deeply incised, dendritic and ramified, highly developed, and apparently very active.

The presence of the continental shelf plays a role in sediment deposition coming from the continent, and the attenuation of the energy from the rivers. The canyons, often disconnected from sub-aerial river systems, are initially formed by mass movements at the slope and evolve up the slope in a second stage by retrogressive erosion [42].

Finally, submarine volcanic eruptions might also lead to submarine volcanic debris-avalanche deposits and turbidity currents. When dealing with the probable position and course of the volcanic eruptions and debris flow, the delineation of valleys and canyons near and around submarine volcanoes becomes important. The orientation of the valleys and canyons might influence potential tsunami waves.

B. Geohazards and Coastal Environmental Impact

While the potential of mass movements can cause tsunami waves, not all subaqueous landslides generate tsunami waves as the energy transfer into wave energy is determined by multiple factors such as the water depth of the landslide, its volume, and the slope gradient which directly influence the initial acceleration and maximum velocity [43]-[45]. Depending on the volume of deposits mobilized by the failure event, the depth at which failure occurs, and the acceleration history of the failed mass, submarine landslides can generate tsunami waves at the sea surface that are known to have a local and damaging effect along the coastline, a few tens of kilometers around the location of the source of the landslide by comparison with earthquake-induced tsunamis that can affect a whole basin [46], [47]. Therefore, only the largest albeit infrequent events are likely to trigger large tsunamis.

Satellite data contribute to a better understanding of the interactions between the coastal morphology and the development of water currents, of course depending on meteorologic and tidal conditions at the acquisition time of the images. Traces of abrasion due to high-energy flood waves have been evidenced near the bay of Arzew. Storm surges or meteo-waves, although generally not as destructive as major tsunami waves occur comparatively more frequently. The influence of sea-level rise due to climatic change has to be considered as well [48], [49]. The Pliocene and Quaternary are ideal time intervals to study sedimentary deposits when high amplitude fluctuations caused variations in sediment supply and played a crucial role in continental margin outbuilding. These fluctuations forced systematic shifts in the position of the shoreline across the continental shelves [44]. Consequently, it is absolutely possible that the 1790 Oran destructive earthquake triggered a tsunami with an epicenter located offshore so here, we have an argument that reinforces the assumption from [11] for the shifting of the shoreline in Oran.

Seismic records available at three Spanish stations suggest that the unexplained waves which killed twelve people in Mostaganem, Algeria in 2007, had a meteorological origin [50]. A first attempt to reproduce these waves was based on potential slides offshore Mostaganem [15]. The preliminary modeling there considered either one or multiple sources in the Alboran and Algero-basin case studies. Seismic records could play an important role in the further understanding of the structure of meteotsunamis [50].

In our investigation, we found that in case of sudden, larger mass movements along the Mazarro Escarpment causing high energetic waves directed towards the south, the affected Algerian coast segments would be prone not only to tsunami waves, but also to motions and perturbation of water-surface-near sediments in the shelf area, and to erosion and subsequent re-deposition of sediments in relatively short time spans. Due to environmental pollution at the coasts, this
sedi
ment perturbation might lead to higher concentrations of polluted material. The return flow with high sediment content has to be considered as well.

Earthquakes in the offshore Alboran domain occur predominantly at a depth of < 10–15 km [51]. In the Gulf of Almeria, a number of earthquakes occurred along the Almeria canyon and channel system. Earthquakes in the central Alboran Sea and those offshore SE Spain generally occurred at a much shallower depth than those in the vicinity of Al Hoceima in northern Morocco. Earthquakes generally occurred above 15 km and most events ruptured between 10 and 2 km [51]. Hence, when strong shaking, even in the context of normal and strike-slip faulting, sediments can be remobilized and provide a triggering factor for local tsunamis offshore. Moreover, seismites have as well been evidenced in western Oranie and the large distribution of the observed deformations within western Oranie (100 km of coastline) suggests a strong source of energy [29], [52]. Finally, the 2016 Alboran seismic sequence with the first shock of magnitude reminds the potential for strong earthquakes in the region with a well-demonstrated threat for tsunami waves reaching the western coast of Algeria not only for thrusting events but for strike-slip motions as well [16], [53].

Directivity of water waves (seismic, aseismic) then constitutes a major threat for environmental hazards in a region where the marine traffic and the oil ports might be a source of toxic substances contamination in the sea and along the coasts.

VI. CONCLUSION

Prone to shallow seismicity and landslide hazard, a study has been there conducted to investigate the coastal environmental impact of geohazards in the Alboran and Algero-Provençal basin, in the western Mediterranean. Marine traffic is particularly dense in this region where the Habibas islands, a preserved archipelago that hosts a unique fauna and flora, is located (northwest of Oran, northwestern Algeria).

The analysis of data compiled from the literature, GIS, and remote sensing showed the role of the tectonic activity and fluctuations in sediment flux from catchment to the basins for pre-conditioning factors for mass movements and local potential tsunami waves in the Alboran and the Algero-Provençal basin. By using this approach, it might be possible to predict more precisely in the case of submarine landslides and turbidity currents in which direction potential tsunami waves might be focused.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

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