MARINE FLOODING HAZARD MAPPING ON THE MOSTAGANEM COASTAL ZONE USING AN EMPIRICAL APPROACH AND GEOSPATIAL TOOLS

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Abstract: Significant global warming, particularly sea level rise, is expected to increase the intensity of marine flooding events on low-lying coastlines. Mostaganem Bay is one of the areas most significantly impacted by this phenomenon. The purpose of this study is to map the risk of marine flooding along the Mostaganem coast. It is based on empirical approach, considering several variables (wave surges, sea level rise and tide). All these variables are integrated within a Geographic Information System. Results show that 13% and 24% of the study area will be at risk of marine flooding, for minimum (8 m) and maximum (9.5 m) inundation levels, respectively. The most affected sectors are expected to be the port of Mostaganem, coastal tourism infrastructure and urban areas. Several adaptation options are proposed to reduce coastal vulnerability to marine flooding; however, these actions should be based on integrated Coastal Zone Management Plans (CZMP).

Key words: sea level rise, marine flooding, coastal hazard, coastal vulnerability

1. INTRODUCTION

Climate change is a major issue today, and we are at a decisive moment (Stigter *et al.*, 2014, Dada *et al.*, 2020). The report of the Intergovernmental Panel on Climate Change shows that human activities have influenced and continue to influence environmental changes (Djalante, 2019). The concentration of greenhouse gases in the atmosphere, including "carbon dioxide, methane, and others", has increased due to human activities. In this context, coastal areas are the most representative regions for socio-economic development, with a growing population (Nicholls *et al.*, 2007).

Coastal areas and their natural environments are exposed to the effects of climate change, particularly sea level rise (Sallaye *et al.*, 2022, Amoura and Dahmani, 2022). Sea level rise is one of the consequences of global warming, primarily due to the melting of polar ice caps and the thermal expansion of water masses. Indeed, global sea level rise will increase the risk of flooding in coastal areas and heighten the vulnerability of coastal populations (Amarni *et al.*, 2021). According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014), total global mean sea level (GMSL) rose at an average rate of 1.7 mm/year during the 20th century. This rate is expected to reach 0.53 m in 2100 according the pessimistic RCP 4.5 scenario (Djalante, 2019) and 0.84 m in 2100 according the RCP 8.5 scenario (Adeniyi, 2016). Sea level rise varies from one place to another on the Earth's surface depending on several factors, the most important of which are winds, pressure, the Earth's movement, and the rate of warming (Tavares *et al.*, 2021). Sea level rise has chemical and physical effects on coastal areas, including coastal erosion, marine flooding, and saline intrusion (Fauzie, 2016).

In recent years, many research efforts have been carried out to map coastal flooding In Algeria, researchers such as (Rabehi *et al.*, 2016; Chaib *et al.*, 2020,) have been working on assessing coastal vulnerability to climate change in the Algerian metropolitan area. In this context, the objective of this paper is to conduct a case study on numerical flood modelling for the coastal city of Mostaganem to identify coastal communities at risk of marine flooding and propose climate change adaptation actions, particularly in response to sea level rise. These actions aim to minimize the negative impacts on the Mostaganem coast, particularly on the low-lying coastal areas such as the Sonacketar zone.

2. STUDY AREA

Mostaganem Bay is located on the west coast of Algeria. The coastline of the study area extends approximately 40 km, between Cape Kef Lasfar on the eastern side and wadi Mactaa on the western side, into which flows a large river known as Wadi Chelif (Senouci *et al.*, 2020). The study area has a total surface area of approximately 163 km^2 from the coastal domain, representing 3.8% of the total area of the Wilaya of Mostaganem, with a population of 102,905 inhabitants (Fig. 1). The analysis of temperature variations was based on the processing of results obtained from data provided by the Climate Research Unit Time Series, available online at Climate Research Unit, covering the period from 1901 to 2019.

The Mostaganem coast is characterized by a Mediterranean climate, with two distinct seasons: the winter season, marked by relatively cold temperatures, has an average minimum temperature of 7.9°C recorded in January. The summer season is characterized by relatively warm temperatures, with an average maximum temperature of 28.8°C observed in August, and the average annual temperature is 17°C (Taibi *et al.*, 2015).

The Mostaganem coastline features presents a remarkable variety of morphosedimentary formations, including estuaries, dunes, beaches, and cliffs. This region is also characterized by a diversity of activities and occupations, making it a densely populated area. Mostaganem's coastal zone is characterized by asymmetry in wave direction and energy, being exposed to waves arriving from the northwest and from the north (Bengoufa *et al.*, 2021).

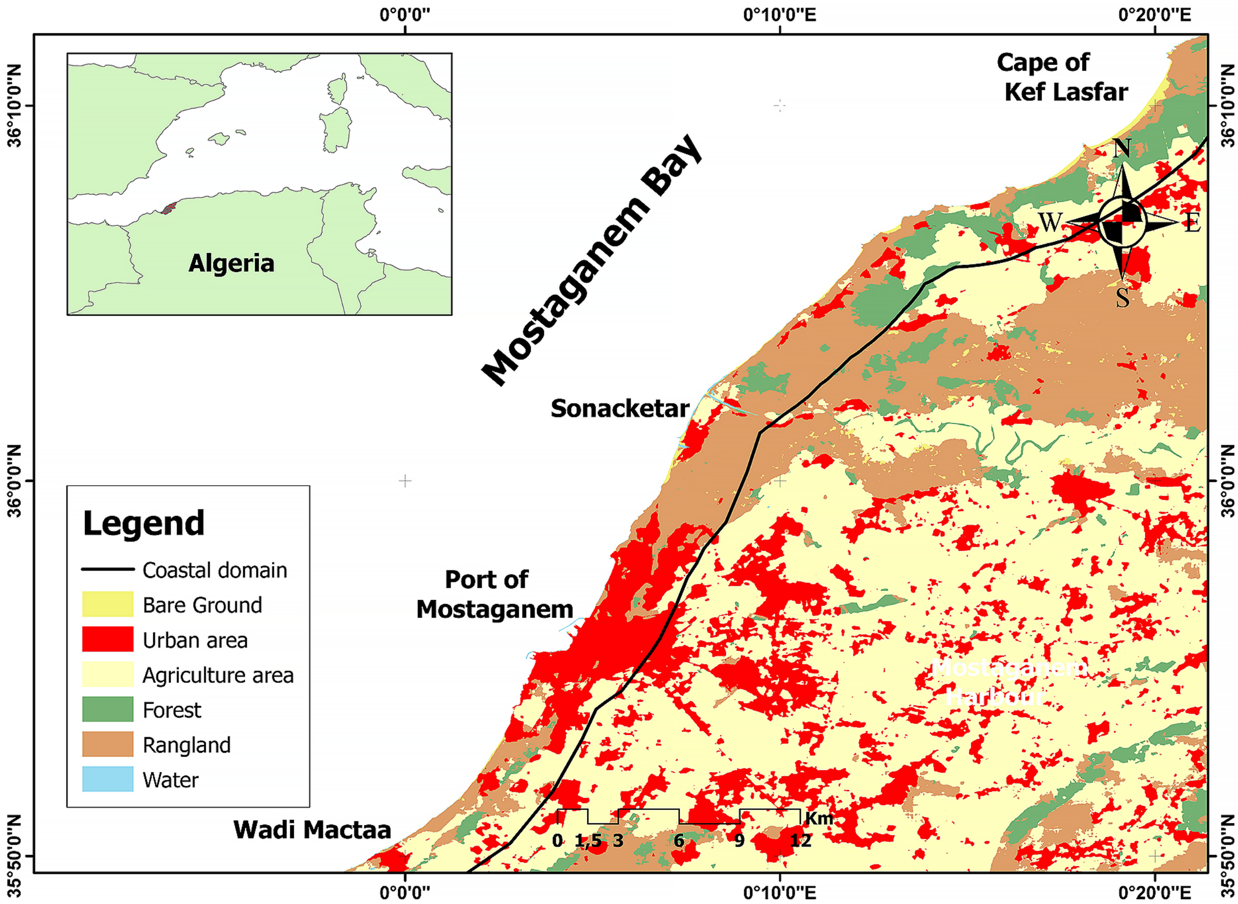

Fig. 1. Geographical location of the study area.

3. MATERIAL AND METHODS

The methodology used in this study is based on direct field observations and simulations using numerical models. Field observations include site-specific data obtained from the Infoplaza Marin Weather (2021) database, available online at www.waveclimate.com.

3.1. Numerical model simulation

For the present study, the Spectral Waves model MIKE 21-SW was used to simulate wave propagation in order to evaluate the pattern of wave energy distribution along the coast (Mezouar *et al.*, 2021).

The MIKE 21-SW model, developed by the Hydraulic Institute Denmark (Mani *et al.*, 2014) is a third-generation spectral wind-wave generation model that simulates the transformation of swells and waves generated by the wind in offshore regions, based on unstructured meshes. The basic equation of this model given in Eq. (1), is written as follows (Kulkarni, 2013) :

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial t}N\cdot c_{g,x}+\frac{\partial}{\partial t}N\cdot c_{g,y}+\frac{\partial}{\partial \theta}N\cdot c_{\theta}+\frac{\partial}{\partial \sigma}N\ c_{\sigma}=\frac{S}{\sigma} \quad (1)$$
$$S=S_{in}+S_{nl4}+S_{ds}+S_{nl3}+S_{bot}+S_{surf}$$

where $N = N(\sigma, \theta)$ denotes the wave action density, with:
θ representing the wave direction and σ the relative frequency;
x and y refer to the geographic coordinates, and t represents time (Cherif *et al.*, 2019);
S represents the total wind energy production.
The components of S include:
Sin – wind energy input,
Snl4 – quadruple wave-wave interaction,
Sds – energy dissipation,
Snl3 – triple wave-wave interaction,
Sbot – bottom friction, and
Ssurf – depth-induced breaking.

The data input for Mike21-2D includes hydrodynamic regime, tides, bathymetry, wind, and offshore wave parameters (Kaiser *et al.*, 2019). The bathymetric data used for Mike21-2D were obtained from the digital bathymetric map available at Navionics site for 2020, as well as from field surveys conducted in Mostaganem Bay in June 2020. The coast of Mostaganem Bay is influenced by waves coming from the north (360°) and the north-northwest (315°), with significant wave heights of 4.94 m and 5.16 m, respectively. The wave periods associated with these directions were 8.10 s and 8.00 s, respectively.

3.2. Coastal flood hazard mapping

To map the risk of marine flooding in coastal areas and analyse the study site, various types of data and information are needed. In the absence of storm surge data, an empirical method has been utilized to estimate extreme sea levels. This method involves using the following formula to estimate and map extreme sea levels along the coastline of Mostaganem (Hoozemans *et al.*, 1993).

$$Dft = MHW + S + Wf + Pf \quad (2)$$

where:
Dft is the inundation level,
MHW is the mean high water level,
S represents relative sea level rise,
Wf is the height of storm surges responsible for flooding, and
Pf is sea-level rise as a function of atmospheric pressure.

3.2.1. Sea level rise scenarios

The assessment of global sea-level variation was conducted through measurements taken by tide gauges. However, due to the unavailability of long-term data for Mostaganem Bay, measurements were obtained using altimetric satellites, specifically TOPEX/Poseidon, since 1992. This approach enabled the estimation of the mean global sea level in the Mediterranean, which has shown an increase of approximately 3 mm per year between 1993 and 2011 (www.nasa.gov).

To determine the impact of sea-level rise on the study area, we established the following two scenarios:

- **Scenario 1**: considered the base scenario, Horizon 2050.
- **Scenario 2**: corresponds to extreme conditions, Horizon 2100.

3.2.2. Coastal topography and land use

To analyse the impact of marine flooding on coastal areas, it is essential to have topographical data available beforehand. The topographic data for our study area were obtained from a Digital Elevation Model (DEM) provided by the National Institute of Cartography and Remote Sensing. The horizontal resolution of the DEM is 0.5 meters, while the vertical resolution is 2 meters (Fig. 2).

3.2.3. The variation of sea level with atmospheric pressure

According to barometric adjustments, sea level can change depending on atmospheric pressure. This relationship can be approximated using the following formula:

$$z = 0.01\times(1013 - p) \quad (3)$$

where p represents atmospheric pressure in hectopascals (hPa).

The increase in sea level is estimated to be approximately 0.10 meters for every 10 hPa reduction in standard barometric pressure (1013 hPa). In the Bay of Mostaganem, the oscillation of atmospheric pressure varied between 952 hPa and 1055 hPa results in a sea level fluctuation ranging from -0.37 meters to +0.61 meters (https://www.wofrance.fr/).

3.2.4. Significant wave height

The wave and wind data comprise altimetry measurements covering a 28-year period (1992-2020). These data were obtained from the Infoplaza Marine Weather database, available at www.waveclimate.com. Statistical analysis of the data was conducted to determine the 100-year wave height associated with waves that cause coastal flooding.

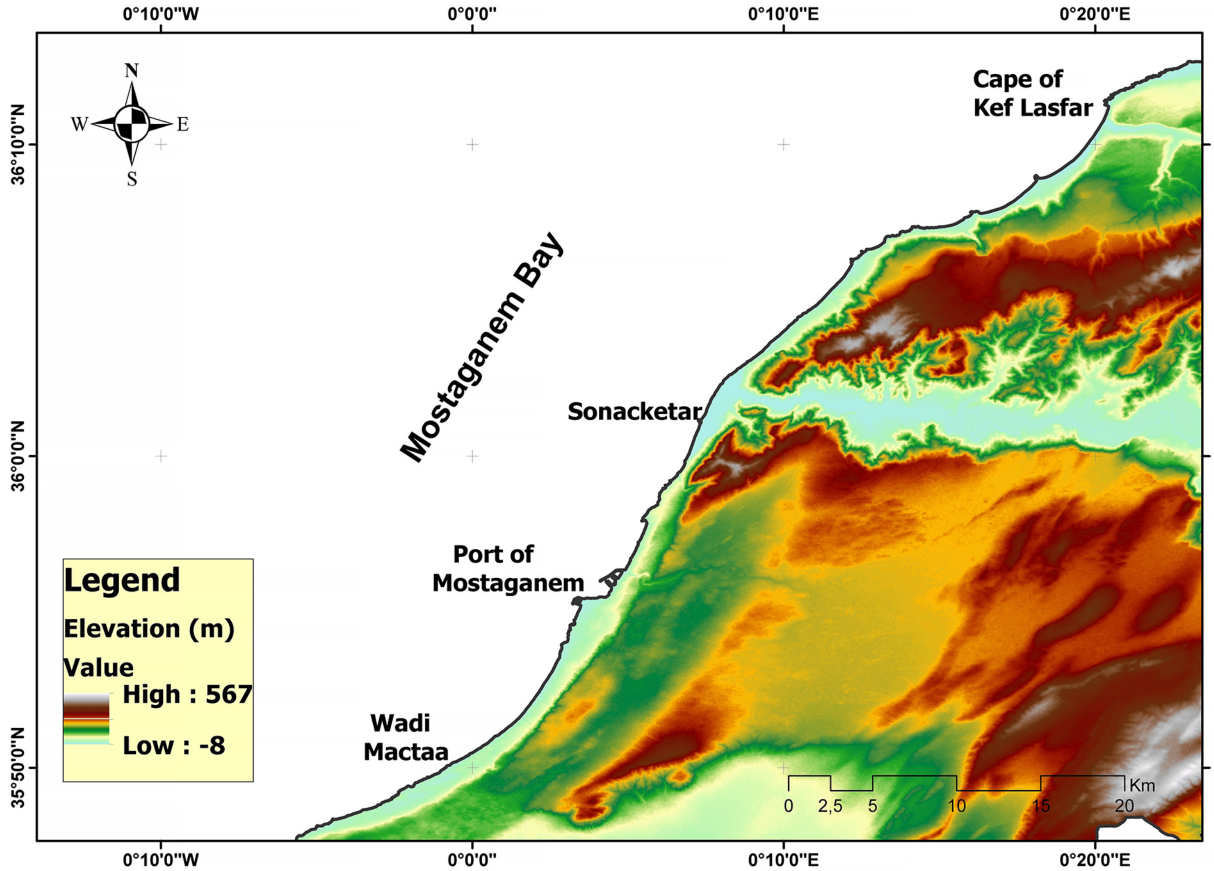

Fig. 2. DEM of the studied area.

Additionally, the analysis allowed the classification of annual occurrence frequencies for significant categories of offshore wave height, according to their direction (Fig. 3).

The processing and analysis of this data indicate that storm surges are infrequent and range between 3.5 and 8.2 meters, while predominant waves of high amplitude range from 0.25 to 3 meters.

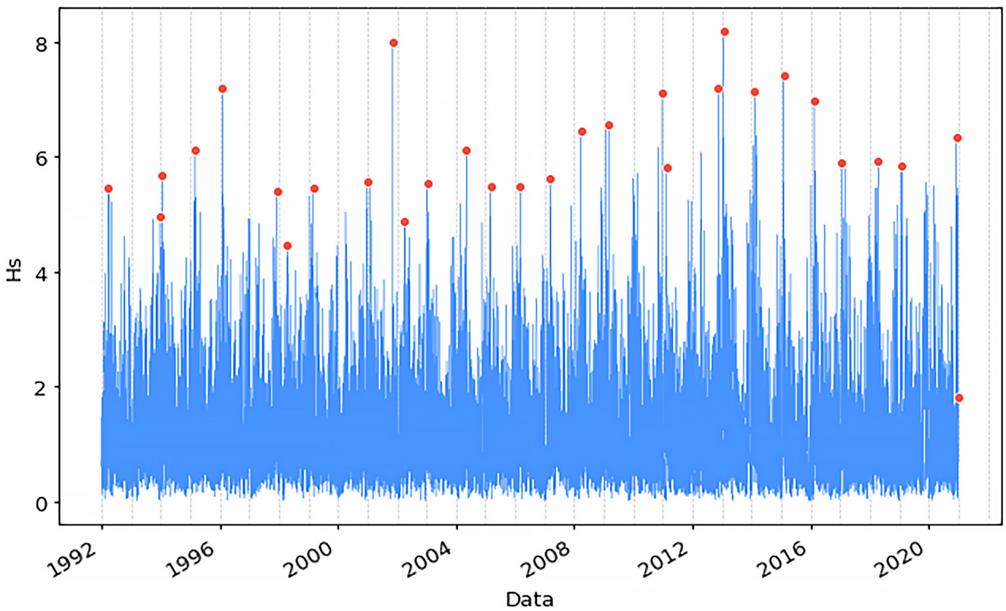

Fig. 3. Significant wave heights in Mostaganem Bay between years 1992-2020.

3.2.5. Extreme wave height

To determine and classify wave events, the Peak-Over-Threshold method was applied to time-series wave data, considering three parameters: an independence criterion, a duration threshold, and a wave height threshold (Walker and Basco, 2011, Hawkes *et al.*, 2008). In our case, we conducted an extreme value analysis (EVA) in Python using the pyextremes platform within a Google Colab notebook (https://colab.research.google.com). After the data analysis, extreme swell amplitudes off the study area were summarized in table 1. Additionally, the extreme wave heights for the study area are presented in figure 4.

Table 1. Extreme wave heights associated with return periods off the coast of Mostaganem.

Return period	Frequency	N	NE	NW	E	W
Annual (m)	1	4.94	3.35	5.16	1.99	4.72
Biennial (m)	2	5.25	3.68	5.68	2.16	5.16
Quinquennial (m)	5	5.75	4.11	6.37	2.39	5.75
Decennial (m)	10	6.31	4.44	6.90	2.57	6.20
Vicennial (m)	20	6.88	4.77	7.42	2.74	6.65
Semicentennial (m)	50	7.62	5.20	8.12	2.97	7.24
Centennial (m)	100	7.85	5.53	8.64	3.14	7.69

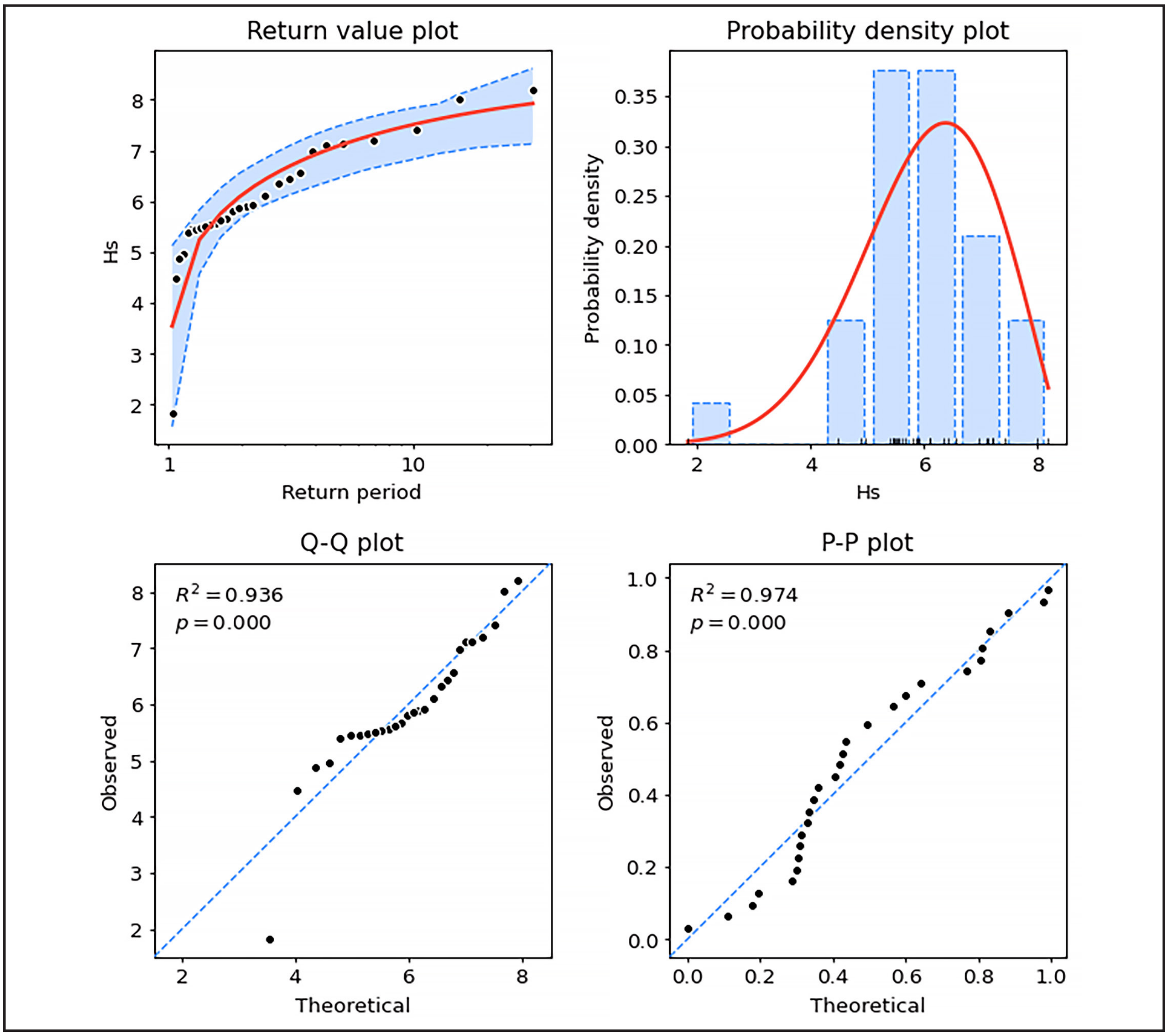

Fig. 4. Extreme Value Analysis.

3.2.6. Extreme waves on the coast

The period and height of extreme waves are determined at the point of breaking. The characteristics of these extreme waves across the shore are assessed using a two-dimensional model (MIKE 21). The simulation takes into account data from the dominant wave directions (N and NW) over 20-year and 100-year amplitudes. The simulation results indicate that the strongest waves originate from the NW, with heights of 7.42 m for a 20-year wave and 8.64 m for a 100-year wave (Fig. 5).

3.2.7. Inundation level estimation on the study area

To estimate the inundation level in our study area, we used the equation of (Hoozemans *et al.*, 1993). Results are presented in Table 2.

4. RESULTS

The Digital Elevation Model (DEM) presented in figure 3 indicates that land with lower altitudes, ranging from zero to 4 meters, is primarily found along the coastal strip, particularly in the low-lying area of Sonakter. Land at altitudes between 4 and 9.5 meters extends further upstream along the Mostaganem coast.

Mapping of flood areas with minimum and maximum flood levels is shown in figure 6. According to table 3, a minimum inundation level of 8 meters could affect approximately 13% of the coastal domain. This land is primarily occupied by the Port of Mostaganem, beaches (including Salamander, Sablette, Metarba, Sidi Madjedoub, and Sonakitar), and coastal defences, which would be nearly completely flooded, along with tourist infrastructure along the coast.

In the case of the maximum flood level (9.5 meters), around 24% of coastal domain would likely be inundated, which is two and a half times the minimum inundation level of 8 meters. The areas most exposed to flooding would include agricultural land (41%).

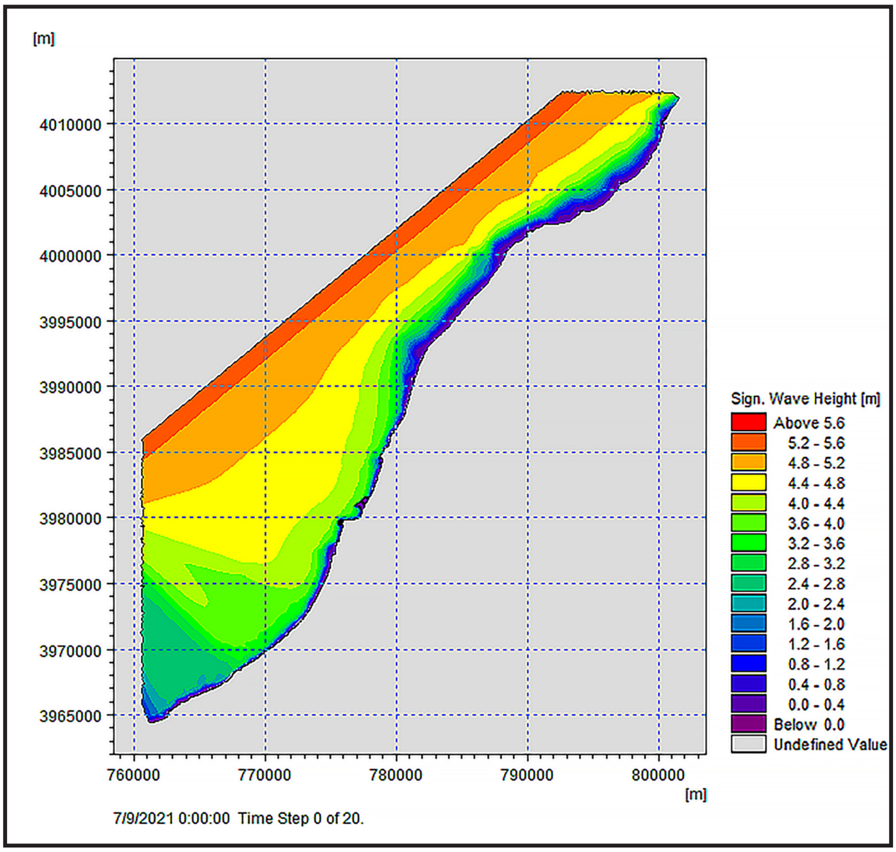

Fig. 5. Simulation of extreme waves from a northwest direction using the mike 21 model.

Table 2. Minimum and maximum inundation levels in 2050 and 2100.

Scenarios	Mean high water level (m)	Sea level rise (m)	Atmospheric depression (m)	Wave surge (m)	Flood level (m)
2050	0.34	0.003	0.61	7.42	≅ 8
2100	0.34	0.003	0.61	8.64	≅ 9.5

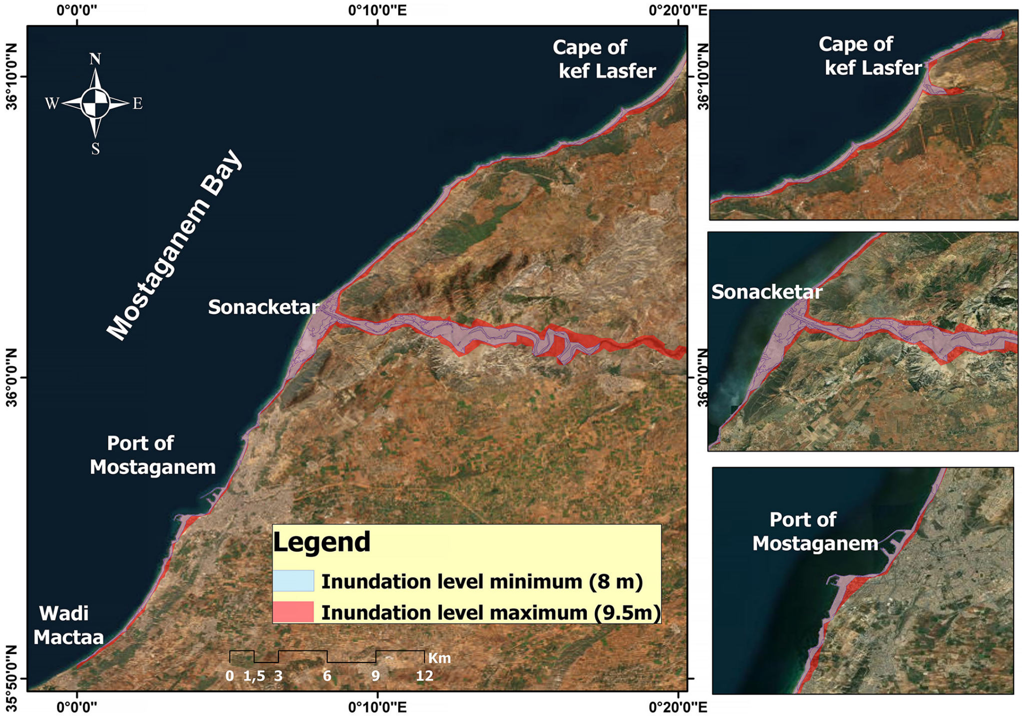

Fig. 6. Marine flooding map with inundation level minimum and maximum.

Table 3. Land loss due to marine flooding in 2050/2100.

Lande use	Inundated areas with the minimum level (8 m) by hectares	Areas (%)	Inundated areas with the maximum level (9.5 m) by hectares	Areas (%)
Water (Wadi Chelif)	30.88	1.36 %	35.84	0.91 %
Forest	153.86	6.79 %	246.56	6.25 %
Agricultural area	826.60	36.47 %	1631.28	41.34 %
Urban area	364.69	16.09 %	568.70	14.41 %
Bare Ground	229.05	10.11 %	244.15	6.19 %
Rangland	661.27	29.18 %	1219.66	30.91 %
Total area	2266.35	100 %	3946.19	100 %

The western part of the bay, where coastal cliffs meet the sea, is less vulnerable to flooding, while the eastern part of the bay features the longest coastline in the study area. This low-lying area is particularly susceptible to flooding, especially following the destruction of coastal dunes for the construction of the Sonachetar power plant figure 7.

Fig. 7. Coastal dunes before and after the construction of the Sonakter power plant.

5. DISCUSSION

Mapping the risk of flooding has not only aided in identifying and delimiting areas vulnerable to future sea-level rise but has also facilitated the assessment of flood zones within the Bay of Mostaganem. Despite the significant variability in simulated climate scenarios and empirical calculations, and considering the potential impacts of sea-level rise on the socio-economic activities in Mostaganem Bay, it is essential to implement an adaptation strategy (Park *et al.*, 2023).

The Algerian government should prioritize adaptation strategies to effectively address the needs of the population, particularly concerning the management of natural hazards and forest resources. In terms of achievements, notable projects and plans have been developed with national support and in collaboration with international partners, focusing on local and sectoral adaptation to climate change (Dahlab *et al.*, 2023).

In September 2015, Algeria submitted its Nationally Determined Contribution (NDC) to the UNFCCC Secretariat. The NDC outlines a target for a national voluntary reduction of greenhouse gas (GHG) emissions by 7% by 2030, based on a Business-as-Usual scenario. This reduction could increase to 22% if Algeria receives international technical and financial support (Dahlab *et al.*, 2023).

Algeria has developed a National Climate Plan (Plan National Climat), with an initial draft completed in 2012. The update of the plan began in 2017, and it was officially adopted in July 2019. This strategic document, created in partnership with the German Cooperation Agency (GIZ), addresses the main challenges Algeria faces regarding climate change (CC) and outlines the necessary mitigation and adaptation measures, particularly in vulnerable sectors such as coastal areas, water resources, and agriculture. The National Climate Plan also presents specific operational actions, along with proposals related to the institutional framework and implementation strategies (Dahlab *et al.*, 2023).

The National Climate Plan outlines a total of 73 actions, of which 5 priority actions have been selected for implementation at the regional or local level Table 4.

Table 4. The key actions of the adaptation to climate change of the national climate plan.

Action	Axe
Capacity Building on Climate Change	Capacity Building
Development of local CC adaptation plans	City and habitat
Strengthening local participation in the planning, implementation and monitoring of actions related to Climate Change adaptation	Capacity Building
Establishment of Climate risk early warning systems	Capacity Building Managing extreme climate events
Protecting maritime infrastructure from erosion (port dredging)	Risk management on the coast

6. CONCLUSIONS

This study aimed to identify and delimit areas most susceptible to future sea-level rise in Mostaganem Bay using GIS and remote sensing. The application of the Houzemans method for assessing the vulnerability of the Mostaganem coastal zone enabled the identification of areas at risk of marine flooding. The Digital Elevation Model (DEM) proved to be a valuable tool for visualizing potential flooding scenarios. By combining land use maps with these flood scenarios, we could precisely identify areas most exposed to inundation. The methodology used in this study can be adapted to other low-lying coastal regions by utilizing data on land use, DEM, and coastal risks.

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