Tsunami Hazard and Area Vulnerability of Mohammedia City in Morocco - Simulation on the Reference Tsunami 1755

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Abstract. The Atlantic coast of Morocco was exposed to the threat of the tsunami and is still threatened by it as a result of earthquakes that occur at the bottom of the Atlantic Ocean, and the city of Mohammedia is located on the Atlantic coast and is an important coastal city that has the largest oil deposits in Morocco and the petroleum port, and important residential neighborhoods.

For this reason, we will try in this article to study the possibility of a tsunami occurring in this city using geographic information systems, and also based on a basic reference to a tsunami that had previously occurred in these areas and was strong, namely the tsunami of 1755 resulting or what is known as the Lisbon earthquake.

In the end, let's draw a map of the danger that would result if such a wave occurred at the present time.

Keywords: Tsunami-GIS-worst case scenario-Inundation Map-1755 tsunami-Mohammedia city

1 Introduction

Tsunami waves are formed by several causes (tectonic acceleration of the sea floor as a result of earthquake - underwater volcanic eruptions - landslides or rockslides that occur either on the sides of submerged volcanoes or rockslides and landslides from nearby coastal cliffs - large meteorites falling into the oceans). An earthquake whose center is under the seabed is one of the most common causes of a tsunami. As a result, a huge amount of sea water moves vertically and suddenly, as shown in the following (**Fig.1**) which causes this water to lose its stagnant and stable state. The earthquake, with spaced intervals between them, may reach several kilometers, heading towards the nearby and far nearby beaches, depending on the strength of the earthquake. These waves can move at a speed of 800 kilometers per hour in deep water, where the wave height is little or no due to the great depth, and over an area of 200 km, and as it approaches the shores (the continental shelf) it begins to rise due to the decrease in depth, and its speed decreases due to friction and braking with the shelf, to reach these waves

To the beaches with a very large height that may reach 30 meters, depending on the strength of the earthquake and its proximity to the beaches, and before the tsunami wave occurs and before the strong waves reach the coast, certain things can be noted that indicate its occurrence, namely [1]:

- Sensation of an earthquake.
- Some gases may come out of the sea water in the form of bubbles.
- The person in the water may feel the water temperature rise directly.
- The beach water recedes inland significantly.

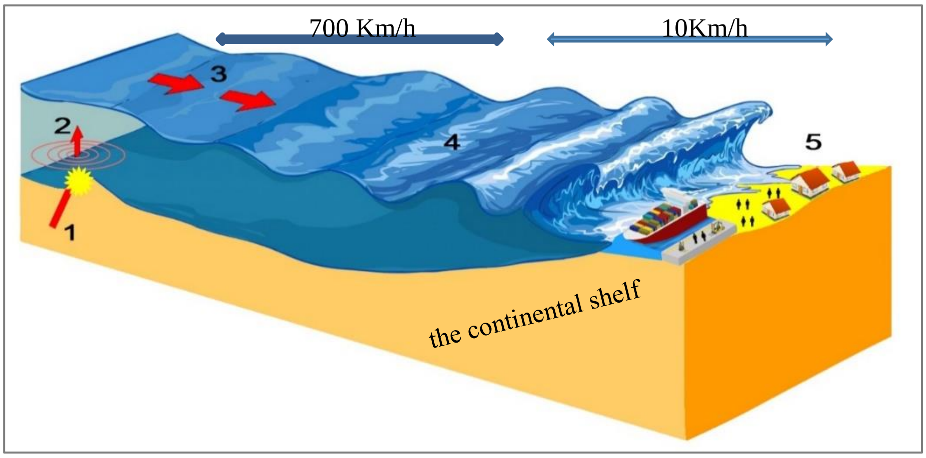


Fig. 1 . Stages of a tsunami wave caused by an earthquake on the sea floor

1: The occurrence of cracking on the sea floor. 2: Water rushes up. 3: The waves are formed and spread quickly towards the shores. 4: As the waves approach the land, their speed slows down and increases in height due to the decrease in depth. 5: The waves rush towards the shores to reach places of the same height, destroying the facilities and buildings in front of them.

2 Study Area

The city of Mohammedia is located on the coast of the Atlantic Ocean, 25 km to the north-east of Casablanca and 65 km south-west of Rabat. The urban perimeter of the city covers an area of 34 km2, between the mouths of El Maleh River in the west and El Nfifikh River to the east, and the motorway axis to the south. The city is bounded to the north by the Atlantic Ocean, to the east and south by the province of *Benslimane* and to the west by the commune of *Aïn Harrouda* (**Fig.2**).

It is located between 7 ° 22 'and 7 ° 25' west longitude and 33 ° 41 'and 33 ° 43' north latitude [2].

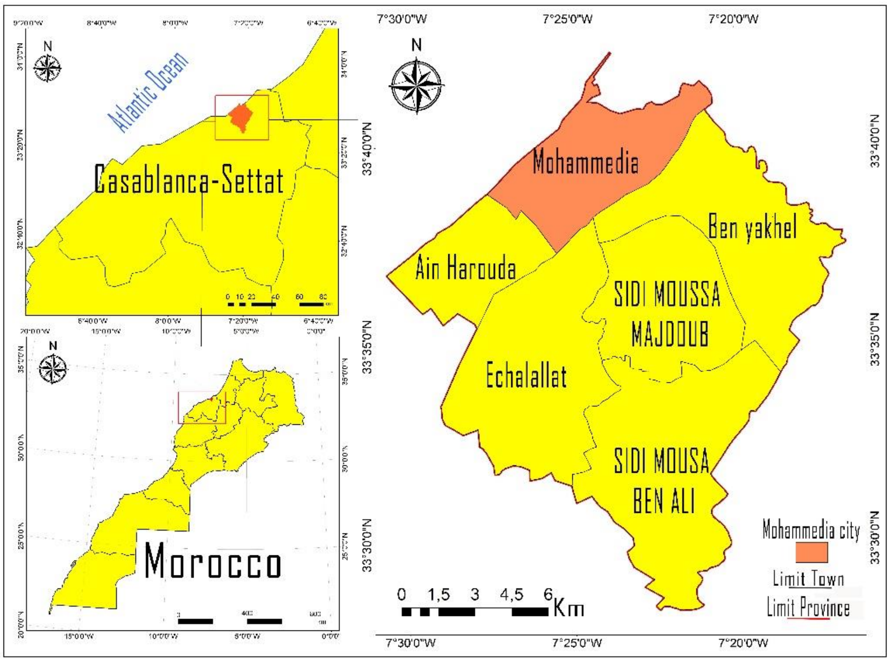


Fig. 2. Location of the city of Mohammedia-Morocco

The topography of the city of Mohammedia consists of two parts:
The Mohammedia plateau and the coastal plain. The area of the city is characterized by a general slope heading from the southeast to the northwest, as elevations are recorded from 56 meters to 25 meters (**Fig.3**) at the borders of the Dead Cliff, which forms a barrier between the plateau and the coastal plain [2].

The coastal plain area is characterized by its flatness at a maximum height of 25 meters, extending from the Dead Cliff towards the coast line, and this area includes the wet area of El Maleh River, estimated at 1,200 hectares, consisting of salt marshes and the mouth of the Salt River, and includes an important biological diversity of plants and birds [2] .

As for the coast line, we can divide it into two parts: a south-western coast extending from cap Mohammedia to the south, consisting mostly of sand and a straight line, in addition to containing humid zone and the mouth of El Maleh River, while the second coast takes a northeastern direction extending from cap Mohammedia towards the mouth of El Nafifikh River It is characterized by the prominence of rocky heads.

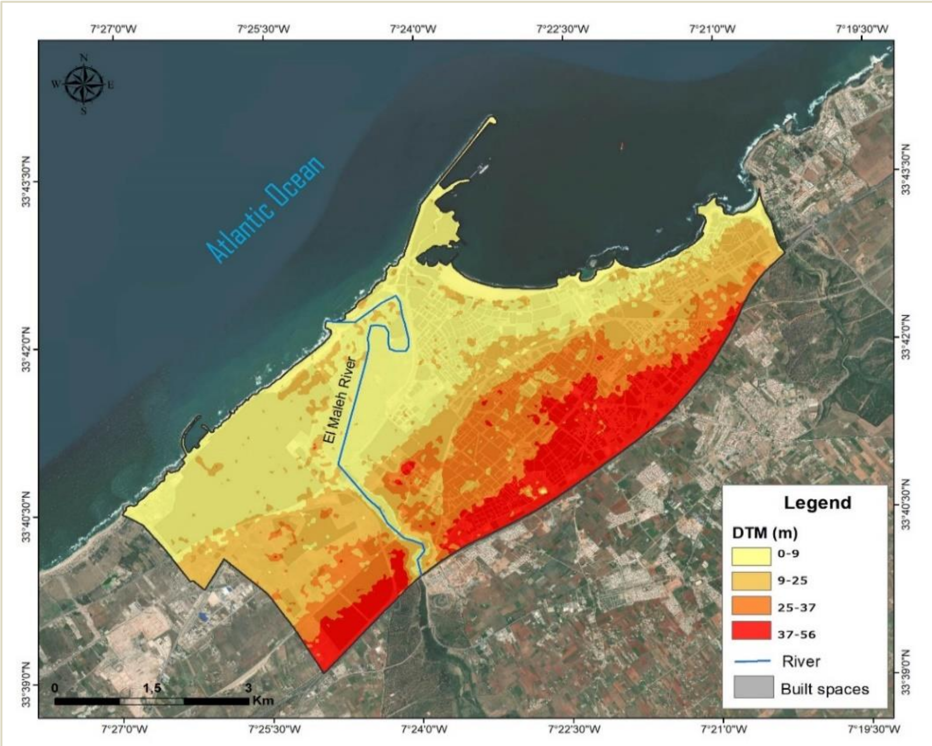
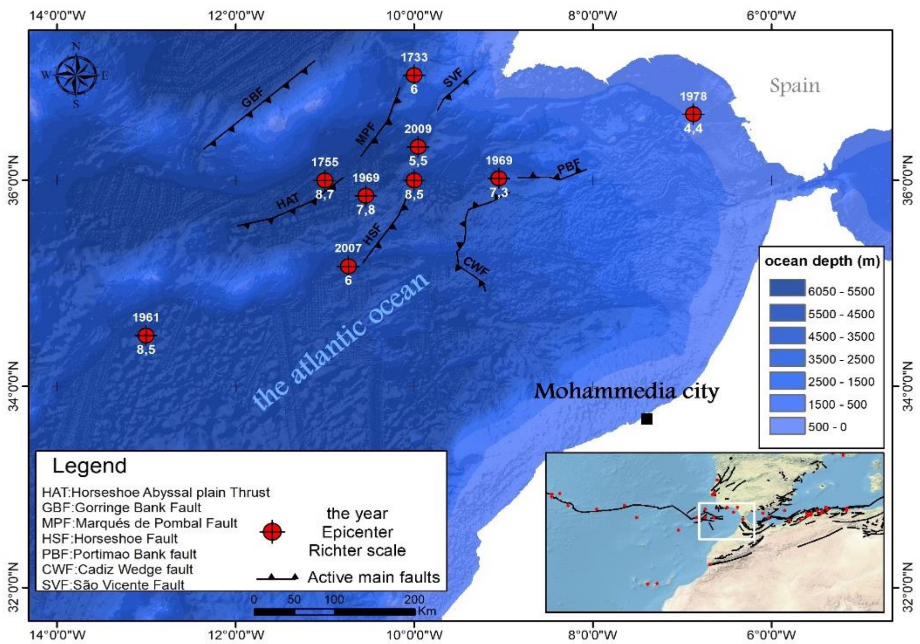


Fig. 3. Digital Terrain Model of Mohammedia City

2.1 Study area and tsunami

The tsunami phenomenon can occur in the Atlantic Ocean region opposite the Moroccan coasts, where the city of Mohammedia is located, and thus the possibility of being exposed to such high sea waves, especially since history mentions that the Moroccan coasts were previously subjected to a tsunami as a result of earthquakes at the seabed, especially faults and active foci that exist In the Iberian Gulf of Kadesh, which is approximately 650 km from the city of Mohammedia, northwest of the Atlantic Ocean, which is the area of convergence of the African and European plate, and one of the most prominent earthquakes that produced very severe tsunami waves is the Lisbon earthquake in 1755. [3]

This scenario is close to ever happening, as a result of plate convergence that produces faults and slips that occur in this bay resulting from earthquakes, and it was determined by 7 active faults that caused previous earthquakes (Fig.4.), and according to simulations of tsunami waves resulting from these faults. It would cause an earthquake with a magnitude of 6 to 8.7 on the Richter scale, which can reach a tsunami wave height of 10 meters, with an estimated time of 21 to 35 minutes to reach. [4]



- Bathymetric Data Gebco .
- Ncei/Wds Global Historical Tsunami Database, 1700 To Present.
- Map Of The Sw Iberian Margin Geological Domains.

Fig. 4. Active faults in the Gulf of Iberian responsible for earthquakes on the sea floor

These faults are distributed northwest of the city of Mohammedia (**Fig.4**), 650 km in the Atlantic Ocean, and are known by the following scientific names: (GBF: Gorringe Bank Fault - MPF: Marqués de Pombal Fault - HSF: Horseshoe Fault - PBF: Portimao Bank Fault - CWF: Cadiz Wedge fault - HAT: Horseshoe Abyssal plain Thrust -SVF: São Vicente Fault), which was and is the cause of many violent earthquakes that caused tsunamis that affected the northwestern coasts of Africa, the western coasts of Europe to Britain, and to a lesser extent the eastern coasts of the Americas Not to mention the islands in the Atlantic[5]. As the map above shows, many earthquakes that resulted in tsunamis occurred in this region as is archived for the years 1733-1755-1969-2007, which occurred with different seismic degrees, the maximum of which was 8.7 and 8.5 on the Richter scale.

The Lisbon earthquake in 1755 is considered one of the largest events in the region, as it resulted in a large tsunami that destroyed cities on the western European and western North African coasts.The fault (HAT: Horseshoe) is the reason for the occurrence of this tsunami, which had a magnitude of 8.7 on the Richter scale, and whose center was the following coordinates (W9.890-, N36.574), with a depth of 4 km under the sea, and the length of this fault is 165 km, and its width 70 km. [6]

3 Materials and Methods

Many studies and historical writings indicated that a seismic earthquake occurred on November 1, 1755, followed by the arrival of high waves on the Moroccan coasts (Tangier: 2.5 metres), (Asilah: 9 metres), (Rabat: 8 metres), (Casablanca: 10 metres), (El Jadida: 9 metres), (Safi: 1.4 metres), (Essaouira: 3 metres). [7]

As for the digital scientific simulation of this tsunami, it relied on many data to derive results about the extent to which the waves reached, and the extent to which they reached relative to the neighboring coasts, As shown in the following table:

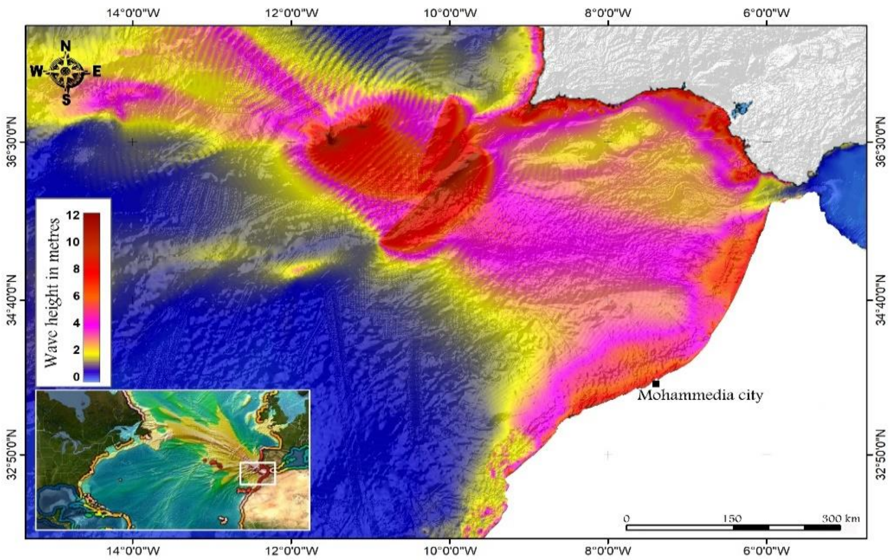
Table 1. Scenario characteristics of the fault responsible for the Lisbon earthquake and tsunami in 1755 (L: the length of the fault in kilometers; W: the width of the fault in kilometers; D: the depth from the bottom of the sea to the top of the fault in kilometres; μ: the shear modulus) [6]

L (km)	W (km)	D (km)	Slip (m)	Strike (°)	Dip (°)	μ (Pa)	Rake (°)	Mw
165	70	4	10.7	42.1	35	3.0×10^{10}	90	8.3

In addition to the morphological study of sediments, fossils, and the chemical study, which showed the presence of layers, sediments and marine components within the continental areas as a result of the marine immersion that transferred these sediments, and this was confirmed by the excavations that included the coastal study in several Moroccan regions (Tangier - Asilah - Larache - Rabat), whose data also coincided with several coastal regions in southern Europe. [8]

All this information and data contributed to the completion of the simulated map of the Lisbon tsunami in 1755, whose results were almost identical to what was circulated in historical writings with differences in some areas.

According to the following map **(Fig.5)**, the data of which was provided by the US National Oceanic and Atmospheric Agency (NOAA) [9], the exposure of the north-western coast of Morocco to tsunami waves with a difference in height ranging between (4, 6, 8 and 10 meters), as for the city of Mohammedia, which is the field of study, the data showed Mohammedia was exposed to tsunami waves with a height of 8 to 10 meters, with a time of arrival of 58 minutes. [10]



- Bathymetric Data Gebco
- Tsunami Forecast Model Animation: Lisbon 1755- Noaa Pacific Tsunami Warning Center, Nasa Blue Marble, 2016.

Fig. 5. Simulation of the height of the waves in the Atlantic Ocean after the tsunami 1755

4 Results

Using these previous data showing the exposure of the Mohammedia city coast to tsunami waves with a height of 8-10 meters, and using the Digital Elevation Model with a high accuracy of 2 meters, Using the (reclassify) tool to classify the areas parallel to the height line of the tsunami waves, the following map was produced that shows scenarios from 0 to 10 meters.

An area of 1644 hectares was calculated as areas below 10 meters in height within the scenario that was used in the above map, and this area constituted 48% of the total area of the city of Mohammedia, and the results were as follows (**Fig.6-7**):

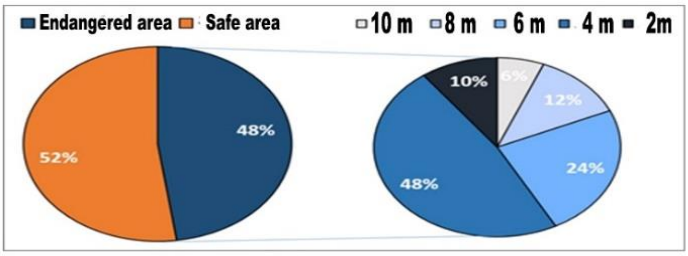


Fig. 6. The distribution of the Mohammedia area according to the scenario of waves height 0-10 meters

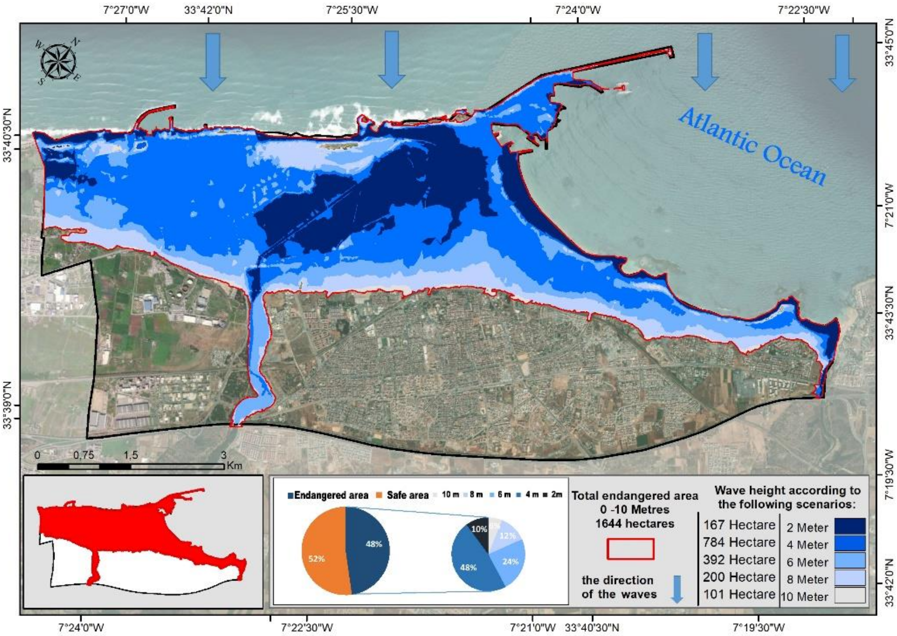


Fig. 7. Projection of the scenarios of waves height (0-10 meters) on the city of Mohammedia

2-0 meters: It included an area estimated at 167 hectares, representing 10% of the area below the 10-meter line, most of which are uninhabited and empty spaces, distributed in the sandy coast line and the wet area, and the southern part of the residential neighborhoods opposite the wet area (Al-Wafa neighborhood).

4-2 meters: This height included 784 hectares, mostly industrial and residential areas and the port, given that the city of Mohammedia is located mostly within this framework of elevations 2-4 meters, Among the most important areas that enter this height, we find the coastal industrial district, which includes facilities and warehouses specialized in petrochemicals, residential and built areas to the east that come directly after the coast line, and the wet area and its eastern areas.

6-4 meters: with an area of 392 hectares, most of which are located behind the previous height inward, and are in a longitudinal shape parallel to Hassan II Street in the east, all the way to the regional road 322 in the west. It also extends with the course of the salty valley to its end at the border of the southern city of Mohammedia, in contact with the oil depots of river el Maleh located on the banks of the river.

8-6 meters: This height is distributed over an area of 200 hectares, and it is somewhat an extension of the previous height, as it takes a longitudinal shape from Hassan II Street to the coastal road, with its presence in some of the higher areas that are found in the part of the coastal industrial zone, And exactly the northern part of the company "Samir".

10-8 meters: This height is distributed over an area of 101 hectares, spread in the scattered areas of the city, especially on the dead shelf that separates the Mohammedia high with the coastal plain where Mohammedia is of origin.

In order to know these projections of the scenario 0-10 meters on the built area, and in order to identify the spatial and infrastructure types threatened by this inundation, the following map was extracted:

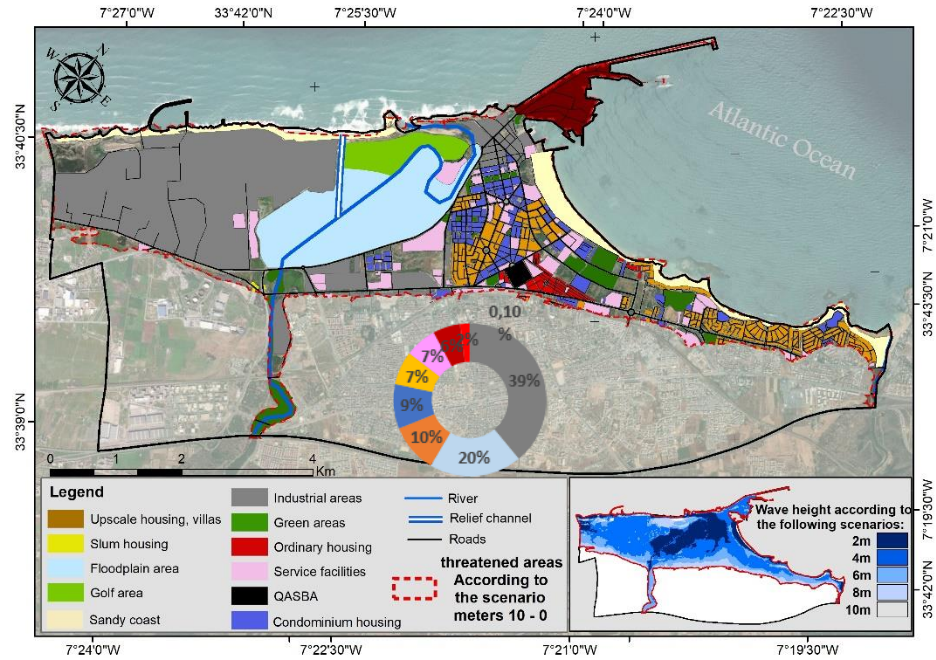


Fig. 8. Categories of threatened areas according to the scenario. Wave heights are 0-10 metres

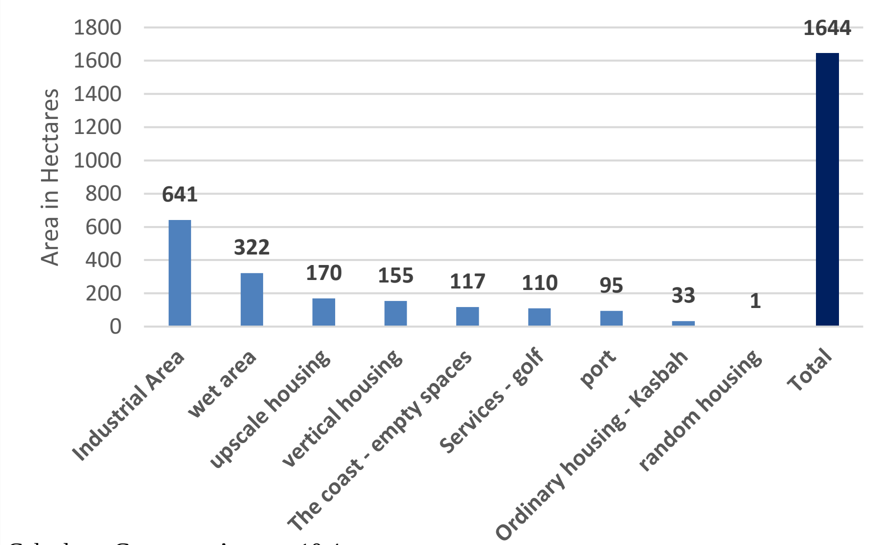
The previously extracted area, which is estimated at 1644 hectares, which is located between 0-10 meters in height, which is the height threatened by sea inundation in the case of tsunami waves of the same height, was projected on the exploitation of the area of the city of Mohammedia, According to the above map, it was found that the various areas, whether inhabited or uninhabited, fall within this scope, and among these areas we find:

The industrial zone, which is considered one of the largest areas threatened by tsunami waves on an area of 39%, and this is represented in the coastal industrial district and the industrial zone of the port because of their proximity to the coast line and also the surface height on which they are located, The area threatened with classification of industrial units is estimated at 641 hectares. As for the areas that include services and utilities, they are threatened on an area of 110 hectares at a rate of 6.7%. The golf club and the Naval Base Club are among the most important facilities that are more and fully exposed.

As for the areas that include residential areas, the high-end housing, which consists of "villas", is threatened with impact on an area of 170 hectares, especially the high-end residential neighborhoods located in the "Monica" and "Manisman" areas. As for the vertical housing, which consists of residential residences, it is distributed over an area threatened by flooding estimated at 155 hectares, most of which are located in the Al-Wafa neighborhood, On the other hand, the estimated area of 33 hectares is the area threatened by flooding, which includes ordinary housing in the areas of “Kasbah” and “Dyour Doukkala” at a rate of 2%.

As for the uninhabited or unbuilt areas, they are also subject to this inundation, as we find the wet area on an area of 322 hectares at a rate of 20%, in addition to the sandy coast and some empty spaces that represent green spaces, all of which are estimated at 117 hectares at a rate of 7.1%,

The following chart (**Fig.9**) shows the arrangement of the areas most likely to be affected by tsunami waves according to the area of marine inundation, by projecting the 0-10 meter scenario on the city of Mohammedia.



Calculator Geometry Arcmap 10.4

Fig. 9. Areas according to the type threatened by flooding according to the scenario Waves 0-10 meters

The same projection is applied to the road network. Through the following map, it has been shown that most of the main and strategic streets that connect the various areas of the city are also threatened by being within a 0-10 meter frame, The main streets that are threatened with flooding have a total length of about 27,870 meters, and they are the ten main streets (**Table.2**), in addition to the internal alleys that water can spread through and which are considered an outlet opposite the coast, not to mention the possibility of affecting 6 barrages.

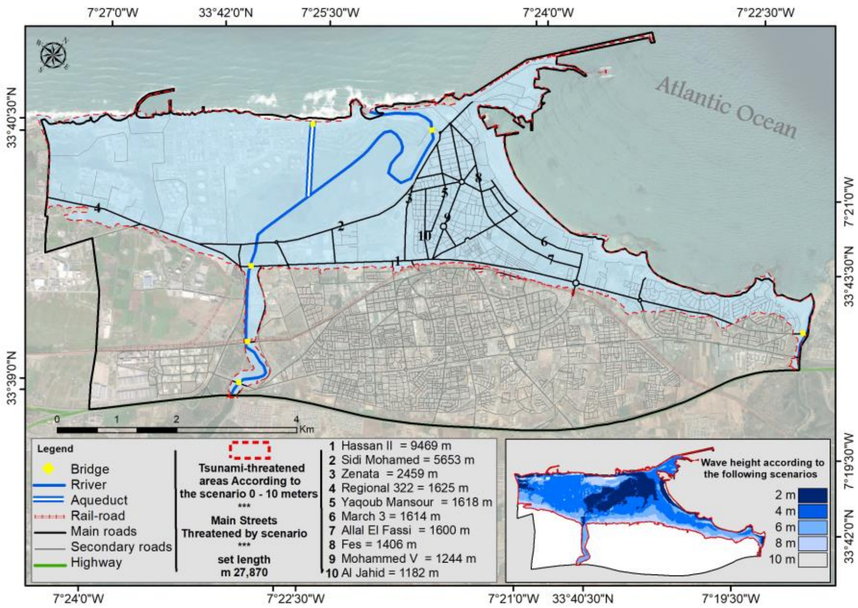


Fig. 10. Map of roads threatened by tsunami flooding

Table 2. The most important main and secondary streets located under the height range 10 meters

Main Streets	Length (m)	Secondary Streets	Length (m)
HASSAN II	9469	ABDERRAHMANE SARGHINI	938
MOHEMMED BEN ABDELLAH	5653	MOULAY ISMAIL	678
ZENATA	2459	ABDEL-MOUMN	941
R322	1625	OUAJDA	824
YACOUB MANSOUR	1618	MOULAY YOUSSEF	742
3 MARS	1614	AGHADIR	577
ALLAL EL-FASSI	1600	IFRAN	563
FES	1406	IBN ZOHR	518
MOHAMMED 5	1244	FARHAN HACHAD	499
EL-JAHID	1182	YOUSSEF BEN TACHFIN	444
Calculator Geometry Arcmap 10.4		RACHIDIA	353
		MALILA	313

5 Discussion

All these previous calculations are only to know the projections, scenarios, the height of the waves on the soil area of the city of Mohammedia In order to perform a digital simulation of the wave height with the height of the area, Using the digital elevation model of the city of Mohammedia (DEM).

But this does not determine to us the degree of damage or the level of danger that can result from this flooding, because the areas and regions in the city of Mohammedia are different, and they do not have the same importance in terms of exploitation, and in terms of the presence of the human factor, and also the presence of the very important petrochemical industrial areas that can The impact of the danger in it is very high if it is exposed to the tsunami waves.

To calculate the degree of risk, it is necessary to create a risk assessment map in order to determine the degree of risk, for this we will work with the following equation[11], which consists of two main components: (H) vulnerability (V) - risk

$$H * V = R \tag{1}$$

Hazard (V): Scenarios of wave heights from 0 to 10 metres.

Vulnerability (H): Classification of areas according to degree of vulnerability.

The objective of creating a risk map and determining the degree of risk (R), is to know if there are material losses, whether it is the destruction of homes, facilities, industrial neighborhoods, or a blockage in the road network. In order to obtain the numerical values of each of the Hazard (V) and the field vulnerability (H) [12], it is necessary to convert their data to the numerical degrees that express them. They are rated on numbers from 5 to 1.

Exploitation of the city field is categorized in order to obtain the numerical values of the field Vulnerability and sensitivity, It was divided into 5 areas according to importance and impact.

The first area, the most sensitive, was for areas and industrial units with petrochemical specialties, such as warehouses, refineries, and laboratories, in addition to the port, as it has the same specialization.

They are followed by the coastal residential areas and their affiliated facilities, as they are the closest to the coast line as the first populated area exposed to waves.

Then it is followed by the inland residential areas that have a greater height than their coastal counterpart, in addition to the uninhabited areas with less Vulnerability such as green spaces, empty spaces and beaches.

The evaluation degree was categorized from the most important or the most severe with the numerical value (5) to the least important and the least severe with the numerical value (1), as shown in the following table 3[13]:

Table 3. Evaluate the values of wave height and field exploitation according to the degree of Hazard and Vulnerability

Hazard (H) Scenarios of wave heights from 0 to 10 metres	Rating score	Vulnerability (V) Classification of areas according to degree of vulnerability	Rating score
0 – 2 m	1	Port Petroleum Industrial Units	5
2 – 4 m	2	Residential And Coastal Areas	4
4 – 6 m	3	Residential And Indoor Built Areas	3
6 – 8 m	4	Green Areas Beaches	2
8 – 10 m	5	Empty Areas	1

After obtaining the numerical evaluation scores for each of the hazard (V) and the field Vulnerability (H), we perform the typesetting or intersection of the values in order to obtain the value (R), through the (Intersect) tool, which is a tool within the Arctool Box tools for Arcmap programs, the goal of which is Extracting the new value through the geometric intersections of the layers and representing them, depending on the equation we are working with.

This process is done by numbering each layer of the drawn layers that indicate a specific exploitation (industrial areas - residential -...), with the reference value obtained in the evaluation table, the same process is applied for the layers of wave height, all this to extract a new layer showing the value The risk expressed in the following table, using the mathematical equation for the levels of risk (R).

Table 4. Matrix score values for each of the Hazard and Vulnerability in order to obtain the degree of risk

	Scenarios of wave heights from 0 to 10 metres				
Classification of areas according to degree of vulnerability	0-2 m 1	2-4 m 2	4-6 m 3	6-8 m 4	8-10 m 5
Port Petroleum Industrial Units 5	5	10	15	20	25
Residential And Coastal Areas 4	4	8	12	16	20
Residential And Indoor Built Areas	3	6	9	12	15

3					
Green Areas –Beaches 2	2	4	6	8	10
Empty Areas 1	1	2	3	4	5

High risk: 10 and more/ Medium risk: 5-9/ Low or no risk: 1-4

The risk levels were categorized into 3 levels (high - medium - low), which are represented on the map by "the levels of danger caused by tsunami waves according to the degree of Hazard and area Vulnerability", These levels have tangible and intangible effects, direct and indirect effects, The direct tangible effects are the direct effect of waves on industrial buildings and industrial infrastructures, wires and pipes, and affecting them through destruction or sabotage, including deaths and injuries,

The indirect, intangible effects are the result of the repercussions of the event, such as the collapse of economic activity, disruption of transportation and telecommunications, etc. [14]

Among the forms of general expression that take into account the (domino) phenomenon, which means the cumulative effect of water on other infrastructures located [15], We represent the risk data (R) on an area of 500 square meters as the average risk in each square, using the (fishnet) tool to create divisions in the layer of risk levels (R), which highlights the geometrical intersections of the layers of Hazard (H) and field Vulnerability (v), as a result Therefore, map (A)(**Fig.10**) was produced showing the level of danger that could result in the occurrence of a tsunami wave with a scenario of 0-10 meters, As for the map (B)(**Fig.10**), it is for the same subject, with a difference in layers, affecting the level of Risk, as it relied on the borders to exploit the field of industrial facilities, residential areas and other spaces.

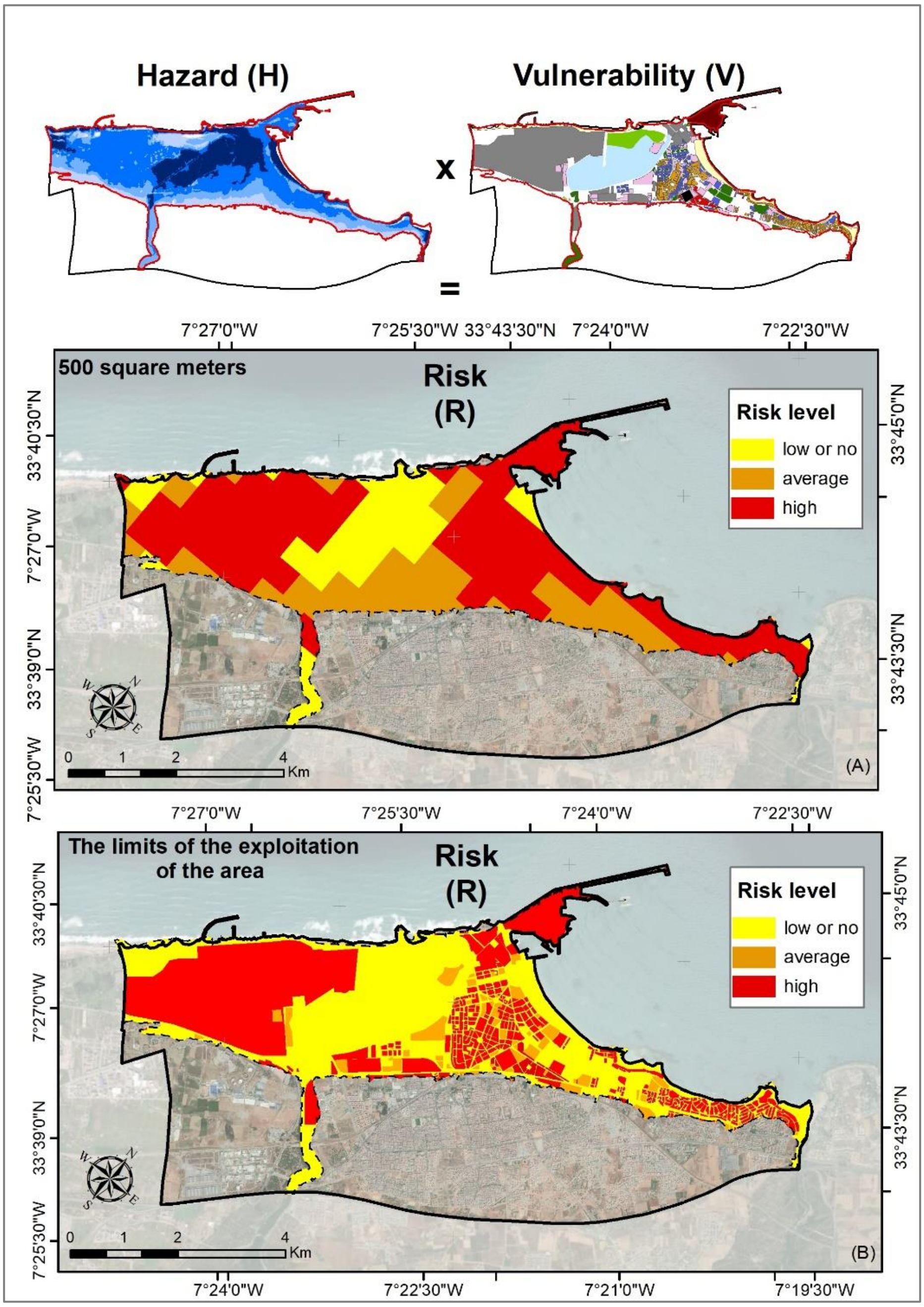
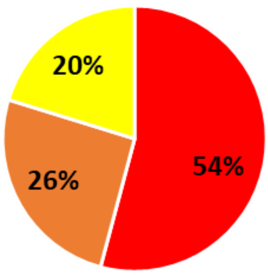
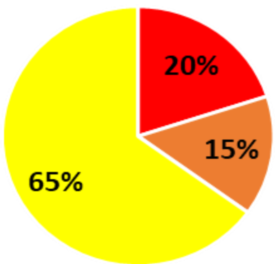


Fig. 11. Levels of Risk resulting from tsunami waves according to the degree of Hazard and area vulnerability.

The results of the levels of risk between maps (a) and (b) were different in the percentage of the area of risk (**Table.5**), So that the introduction of the effect of (Domino) has increased the level of risk, especially in the high category, This is as a result of the presence of some facilities that will affect the surroundings of their own, such as warehouses, gas and oil pipelines, and sensitive industrial facilities that can cause a second, indirect danger due to the destruction of these units, due to which petrochemical leaks can occur, and thus the occurrence of explosions and fires, especially in the region South of the city, where the industrial units are located, and the port area.

Table 5. The type of Risk by level, depending on the map (A) and (B)

Map	Tangible Effects By Risk (R)
A 	Flooding - Oil, Gas And Chemical Spills And Explosions - Destruction Of Houses - Erosion Of Soil And Trees - Interruption Of Power And Communication Lines - Difficulty In Movement - Water Pollution
	Destruction Of Houses - Difficulty Of Movement - Flooding - Erosion Of Soil And Trees - Interruption Of Electricity And Communication Lines
B 	Erosion Of Soil And Trees - Flood -

6 Conclusion

Simulations that depend on historical events such as the tsunami in 1755 indicate that the city of Mohammedia is highly exposed to this Risk, with the help and use of GIS that showed the areas most exposed to waves, Especially the very im-portant petroleum zone. So now it is necessary for the officials to work on think-ing about protecting these facilities and developing plans to build barriers or something like that, It is also important to educate the population and how to protection them and evacuate the city in case there is a direct and confirmed threat. because hough the issue of alerting does not save much time, an hour at most Is an hour enough to evacuate the population from the threatened areas?

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