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Quantitative risk assessment in El-Jadida (Northern Atlantic Coast of Morocco) for a tsunami scenario equivalent to that of the 1755 Lisbon earthquake

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Abstract

The Atlantic coasts of Morocco are exposed to tsunami risk. Although this risk level is low because of the rarity of tsunamis in the region, a future event would be catastrophic for the Moroccan society and economy because of the numerous issues at stake. In this paper, bathymetric/topographic data and parameters of three known tsunamigenic faults (Marquês do Pombal Fault, Gorringe Bank Fault and Horseshoe Fault) were used to simulate a potential tsunami event in the city of El-Jadida (Morocco) using MIRON software. The simulation results of the worst-case scenario were then exploited to perform a quantitative risk assessment, using demographic and economic input data. Results show that choosing the Horseshoe Fault as source of the simulated event produces the largest tsunamis; with maximum wave heights ranging from 10 m to 27 m. These results are found to be consistent with historical records and computer model simulations from previous studies. Quantitative risk assessment results indicate that the city of El-Jadida is exposed to a high risk of loss of lives and properties with values of the order of 34 lives/yr and 14M\$/yr respectively. For this reason, we underline the dire need for the implementation of tsunami risk prevention and mitigation strategies that should prioritize the protection of high-risk areas of the city and its population from a possible future catastrophic event.

Keywords: Tsunami, Simulation, Quantitative Risk Assessment, Atlantic coasts, Morocco.

1. Introduction

Tsunami is one of the deadliest natural hazards, claiming hundreds of thousands of lives all around the world (e.g., Bernard *et al.* 1988; Doocy *et al.* 2007). In addition, tsunami events also constitute a great risk to coastal regions increasingly impacted by different human activities. For instance, the tsunami of December 26th 2004 killed more than 300 000 people and caused economic damage exceeding \$10 billion to countries surrounding the Indian Ocean (Sharpley 2005). This disaster has spurred scientific research with aim of better understanding tsunamis and their potential economic, environmental and societal impacts.

In the Gulf of Cadiz (Fig.1), with the exception of some small tsunami waves generated by the 1969 earthquake (Baptista *et al.* 1992), no tsunami events were experienced during course of the twentieth century. However, the massive destruction caused by tsunami waves associated with the historical 1755 Lisbon earthquake (Levret 1991), strongly highlights the exposure of the this region to this hazard and its proneness to produce catastrophic events in the future (Baptista *et al.* 1998; Gutscher *et al.* 2006).

To simulate possible future occurrences, computer models were run based on the characteristics of potential tsunamigenic seismic sources located in the Gulf of Cadiz (e.g. Barkan *et al.* 2009; Font *et al.* 2010). In all of these studies, the destructiveness of probable future tsunamis for the U.S, Spanish and Portuguese coasts was demonstrated. From a socioeconomic point of view, such events would be disastrous for Morocco as well, given that a large portion of its population (10.3 million people) (Laouina 2019), and large segments of its economy are tied to important coastal cities alongside its Atlantic shoreline. For this reason, several studies have attempted to evaluate the impact of a potential tsunami on some of the populous (i.e., Casablanca, Rabat and El-Jadida; see for example Omira *et al.* 2009; Mellas *et al.* 2012; Moussaoui *et al.* 2017), but these studies have been limited to qualitative risk assessments. Such methods are subjective and lack a numerical basis for the estimation of potential economic and societal losses. Conversely, Quantitative Risk Assessment (QRA) methods are more objective and produce more realistic estimations of the tsunami impact because they elicit measurable quantitative data from experts, without simply relying on the expert's opinion (Jelínek and Krausmann 2008).

To choose one approach over the other, one has to consider the objectives of the study. In fact, qualitative risk assessment methods are limited to national and regional scale zonation efforts aiming to determine high risk areas on which quantitative assessments need to be performed using higher resolution data. The latter approach is found to be more useful for decision makers since it allows a better risk-to-reward assessment for planning and funding of mitigation strategies and programs (Saunders and Glassey 2007). In scenario based QRA studies conducted from a human perspective, one has to first characterize the spatio-temporal hazard, then estimate the issues at stake and finally assess their vulnerability to the catastrophic event (Granger *et al.* 1998; Papathoma *et al.* 2003; Nadim 2006; Post *et al.* 2009; Jelínek *et al.* 2012). For tsunami hazard characterization, the mapping of tsunamogenic faults (source area) and tsunami propagation geometry can be performed using a variety of simulation softwares, while the vulnerability assessment can be done using different methods, depending on the objectives of the study and data availability.

In effect, to conduct an accurate QRA, simulation results obtained using a robust algorithm must be used as input data. However, most tsunami simulation softwares are expensive and thus not accessible to all researchers, especially in developing countries. Conversely, MIRONE simulation software, which is a free and open-source alternative capable of simulating tsunami events with reasonable accuracy (Luis 2007), constitutes a cost-effective alternative to model tsunami wave propagation and wave heights both offshore and on land. This tool adopts the Mansinha and Smylie (1971) equation which uses fault geometry, the bathymetry of the area and the

triggering earthquake magnitude as input data. Such information can be drawn from previous geological studies as well as digital elevation models available online.

QRA only measures the immediate damage caused by a given tsunami, without taking into consideration post-disaster rescue operations, and their role in aggravating or diminishing the overall death toll and number of missing people. This was demonstrated in the 2004 tsunami where patient transport efforts and medical rescue coordination and infrastructure allowed rescuing hundreds of lives (Li and Zheng 2014).

In this paper, we conducted a tsunami simulation using MIRONE, combined with demographic and economic data to establish a QRA for the city of El-Jadida (Fig.1). This area was chosen because it was devastated by tsunami waves generated during the 1755 Lisbon event, as reported by Soyris (1755). The aim of this paper is to propose a time-saving low-cost tsunami QRA method capable of helping decision makers to develop better strategies for tsunami risk mitigation, based on objective and quantifiable datasets.

2. Study area :

2.1. Seismic setting and tsunamigenic faults in the Gulf of Cadiz.

The Gulf of Cadiz is characterized by a high-level of seismic activity related to convergence at the poorly defined, Eurasia-Africa plate boundary (Fig. 1A) (e.g. Matias *et al.* 2013). In some cases, regional seismic events can generate large tsunamis, such as the Lisbon earthquake of 1755 ($M = 8.5-9$), which is considered the strongest ever recorded seismic event in western Europe (Fig. 1B) (Levret 1991; Baptista *et al.* 1998; Gutscher *et al.* 2006). Despite a significant magnitude ($M_w = 7.8$) (Fukao 1973), the second largest seismic event that struck the Gulf of Cadiz and its surrounding coasts in 1969 only generated small tsunamis waves (Baptista *et al.* 1992). More recently, some lower-magnitude seismic events occurred in 2003 ($M_w = 5.3$), 2007 ($M_w = 5.9$) and 2009 ($M_w = 5.5$), but they did not generate tsunamis in the region (Pro *et al.* 2013). Following these events, no earthquake with M_w greater than 6 has been recorded (Matias *et al.* 2013).

In the Gulf of Cadiz, instrumental earthquake data show that the region is tectonically active with most focal points being concentrated alongside active faults in the region (Fig. 1). The focal mechanisms retrieved from the Harvard Global centroid moment tensor catalogue (Ekström *et al.* 2012), show that most events, which can be related to the same tectonics responsible for the 1755 event, are caused by compound reverse strike-slip or pure strike-slip motion (Fig.1) (e.g. Pro *et al.* 2013).

The locations of some of the recent earthquake epicenters can be determined with more accuracy (Fig. 1). Nevertheless, that of the 1755 event is still a matter of debate in the scientific community. To tackle this,

104 intensity maps of the 1755 earthquake were compared to those of the 1969 event (e.g. Levret 1991; Bufo et al.
105 2020) and to macro-seismic (Solares and Arroyo 2004) and micro-seismic (Silva et al., 2017) data recorded
106 during the twentieth century. The findings of these studies suggest that the most probable epicenter location of
107 the 1755 event is to the southwest of Cape Saint-Vincent (Fig.1), and that the 1969 and 1755 could be associated
108 with the same seismogenic source (Levret 1991). However, according to Johnston (1996) and Hayward et al.
109 (1999) the 1755 epicenter location could also be the Gorringe Bank because of the presence of active NNE to NE
110 trending thrust faults related to submarine tectonic uplift (Gorringe Bank Fault). The region of Marquês do
111 Pombal also qualifies as a possible location for the Lisbon event's epicenter, where an active fault could be a
112 potential source (Zitellini et al. 1999, 2001). In addition, the seismicity is also not spatially correlated with
113 surficial fault zones in this area, (deep earthquakes 20 to 40 km). Yet, Bufo et al. (2020) suggested that the NE
114 trending thrust fault known as the Horseshoe Fault, which is characterized by a continual occurrence of seismic
115 events (2003, 2007 and 2009) (Pro et al. 2013) (Fig.1), is much more likely to be the source of the 1755
116 tsunamigenic earthquake.

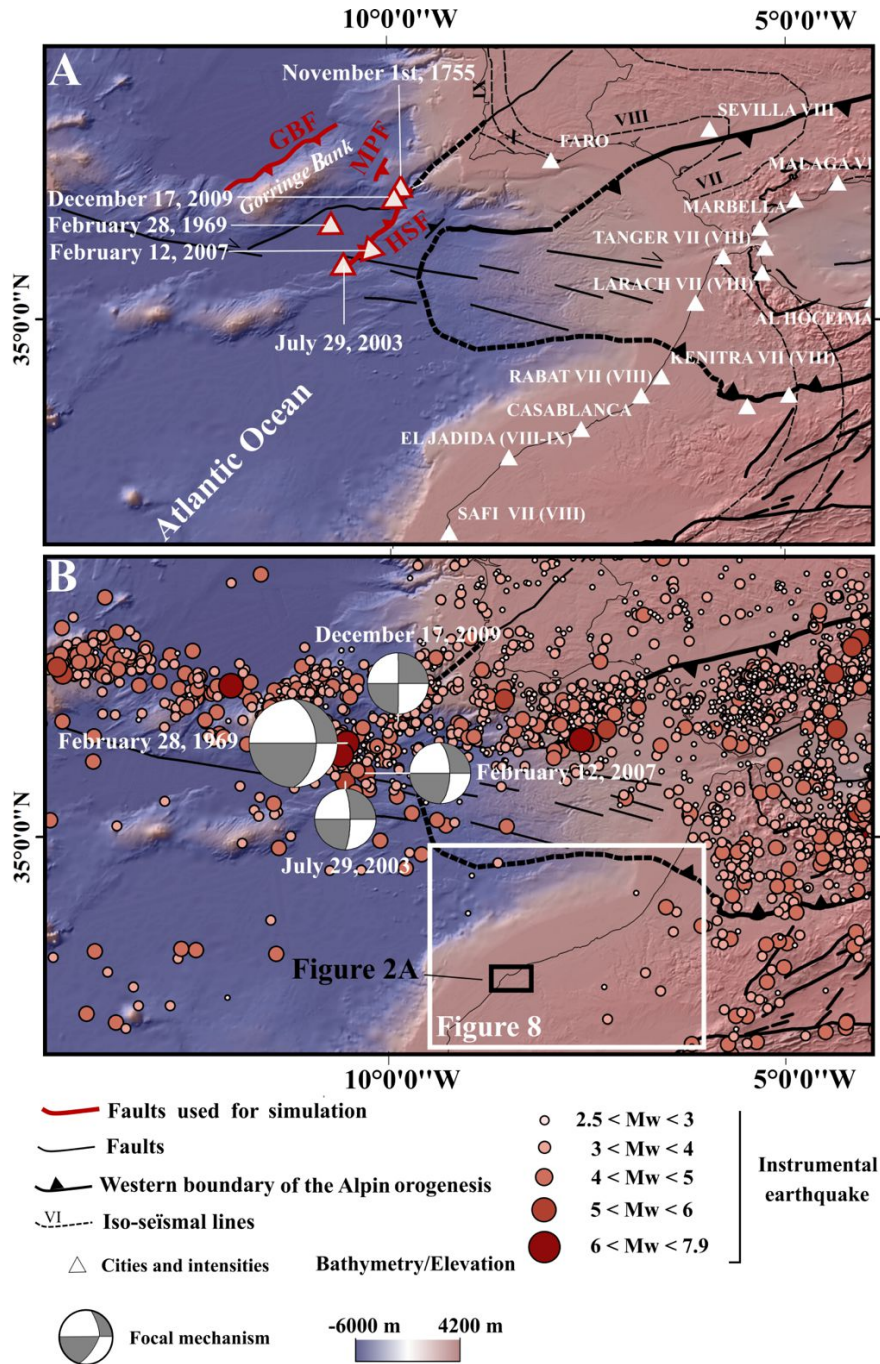


Figure 1: Geodynamic setting of the Gulf of Cadiz and its surrounding areas. (A) Major active structures proposed as the possible source of the 1755 tsunamigenic earthquake event (GBF, Goringe Bank Fault; MPF, Marquês do Pombal Fault; HSF, Horseshoe Fault), associated with isoseismic lines (MSK Scale) showing its effects on the Moroccan and Iberian regions (from Levret 1991). Red triangles indicate the location of earthquake events discussed in this section. (B) Seismotectonic map of the Gulf of Cadiz and its surrounding areas. The instrumental data is from International Seismological Center (2020) and focal mechanisms from Harvard global centroid moment tensor catalog (Ekström et al. 2012). Locations of figures 2 and 8 are shown.

2.2. Tsunamis in Morocco

Morocco is vulnerable to coastal hazards because its most economically influential cities are located alongside its Atlantic and Mediterranean shorelines. In addition to storms, coastal erosion, and sea level rise, tsunamis constitute the most dangerous coastal hazard threatening these newly-constructed human settlements in the area (Blanc 2009; Omira *et al.* 2010; Atillah *et al.* 2011; Renou *et al.* 2011). In fact, the impact of past occurrences, such as that of 1755, have been documented in old towns that have now grown into big cities close to, or on, the Atlantic shoreline (El Mrabet 2005; Blanc 2009). Several attempts to model the effects of these events and to estimate the risk to human life and goods, show that the region is widely exposed if similar events were to recur (Omira *et al.* 2010; Atillah *et al.* 2011; Renou *et al.* 2011; Mellas *et al.* 2012; Moussaoui *et al.* 2017; Ramalho *et al.* 2018). In addition to historical documents, material evidence (geomorphic and sedimentary indices) for tsunamis or high energy events in Morocco have been found in many sites alongside the Moroccan Atlantic coast: (1) in Larache and Rabat (Medina *et al.* 2011), (2) Tahadart estuary (Talibi *et al.* 2016; Khalfaoui *et al.* 2020) and (3) close to the Loukkos river mouth, (Mhammdi and Medina, 2015). According to Soyris (1755), the Lisbon earthquake of 1755, the intensity of which reached VIII-XI on the Mercali scale, produced a large tsunami wave that affected northern Morocco, with El-Jadida city being one of the most impacted (Levret 1991). Other descriptive data, as well as tsunami hazard assessments performed using simulations agree on the great impact of this event on El-Jadida city (e.g. Blanc 2009; Ramalho *et al.* 2018).

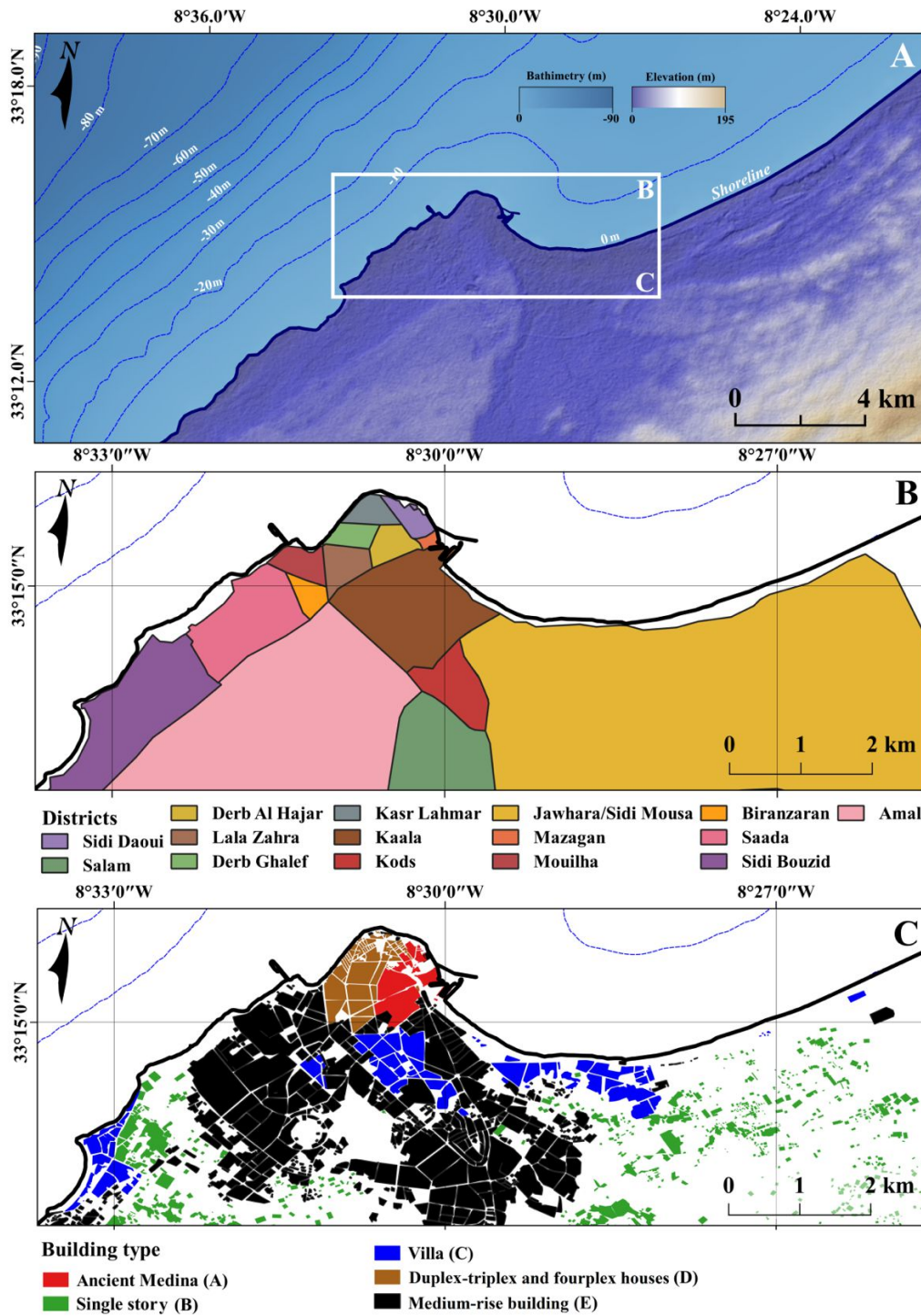
2.3. Socio-economic setting of El-Jadida

The largest and most important cities for the Moroccan economy (nearly 66% of its total Gross Domestic Product (GDP)) are located along its Atlantic coast (D.A.T. 2017). As such, any tsunami should have a long-lasting catastrophic impact on the economy of the country. Nevertheless, despite natural disasters causing negative economic consequences in most areas of the world, and at best a full recovery and return to the previous state of affairs after years to few decades (Cavallo *et al.* 2013), some events can trigger economic growth by generating aid from international institutions and governments. A fine example is the Asian tsunami of 2004, which turned out to be an iconic case of international cooperation and solidarity in the face of natural catastrophes (Cavallo and Noy 2011; Loayza *et al.* 2012; Heger and Neumayer 2019).

El-Jadida city is characterized by a high level of exposure and vulnerability to tsunami events because of : (1) the poor design of its marine defense structures (Omira *et al.* 2013); (2) its high population density with ≈ 7000 inhabitants/km² (H.C.P. 2014); (3) the low level of education (86.5 % of El-Jadida population is below level 3 of

154 the international education standard, 23.3 % being illiterate (H.C.P. 2014); (4) the relatively high percentage of
155 residents aged 55 or older (13% of El-Jadida's, i.e. for 25,000 people (H.C.P. 2014); (5) and the fact that most of
156 El-Jadida's buildings are located within 3 km from the Atlantic shoreline, on relatively flat terrain (Fig. 2).

157 Regarding construction practices in the study area, all buildings can be grouped into five major categories based
158 on practices and materials, the number of storeys and the reference unit-price for each square meter (Fig. 2-C,
159 Fig.3 and Fig.4). The first type (ancient Medina), which dominates in Cape Mazagan, dates back to the Middle
160 Ages and differs considerably from other districts (UNESCO 2004). Despite its oldness, the Mazagan district can
161 be considered as one of the least vulnerable sites because it was built on relatively elevated land (altitude > 6 m)
162 (Fig.4-f). Other newly built districts are constructed using reinforced concrete and do not have any protection
163 against coastal hazards (Fig. 3).



164

165 Figure 2: (A) Topography of El-Jadida city and surrounding areas and offshore bathymetry. Topography from
 166 the ALOS PALSAR Digital elevation model is used (<https://search.asf.alaska.edu>, accessed December 2020),
 167 and bathymetry extracted from the GEBCO database
 168 (https://www.gebco.net/data_and_products/gridded_bathymetry_data/, accessed December 2019) (B) Spatial
 169 distribution of El-Jadida city districts. (C) Spatial distribution of El-Jadida building types
 170 (<https://maps.google.com>, accessed December 2020).



Figure 3: The beach topography of El-Jadida city and the location of major building types, which represent the first elements to face the tsunami hazard.

In addition, the construction types greatly influence the population density values. For instance, villas (Fig.4-c) are characterized by a very low population density, in contrast to the ancient medina (Fig.4-a) and medium-rise-buildings (Fig.4-e). As for single storeys, duplex-triplex and fourplex houses (Fig.4-b-d), a lower density is also expected.



Figure 4: The main types of building types of El-Jadida city: (a) ancient Medina; (b) single-story buildings; (c) villa; (d) duplex-triplex and fourplex houses; (e) medium-rise buildings; (f) the marine protection wall of the ancient Medina.

3. Material and Methods

In this study, we adopted a new approach to QRA (Fig. 5), based on the exploitation of simulation results to assess tsunami risk calculate using the Fell et al. (2005) assessment system.

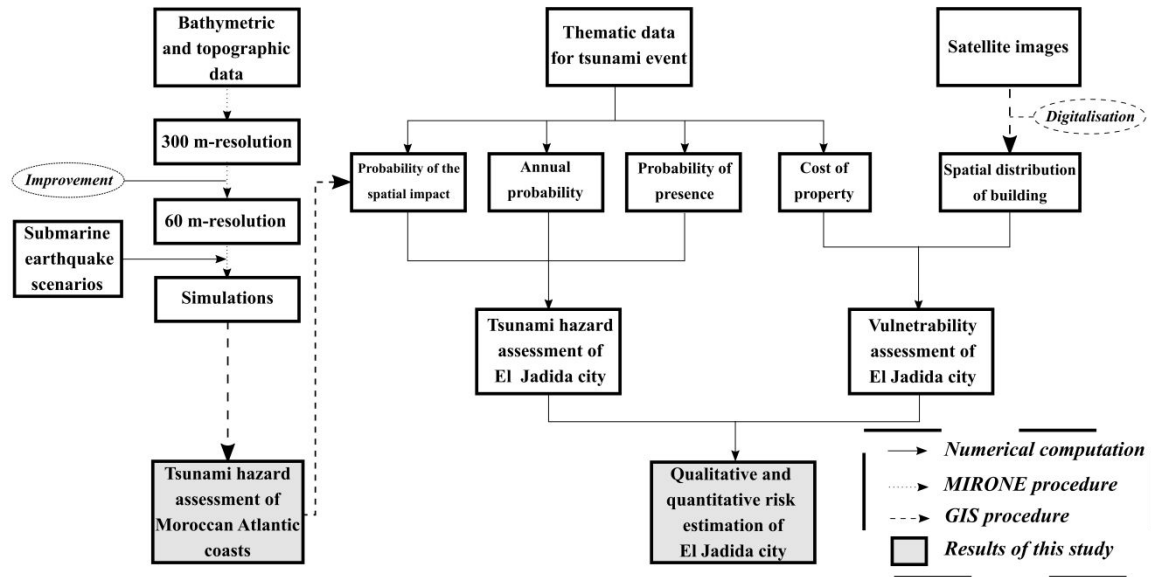


Figure 5: Logical approach adopted to evaluate the tsunami risk in El-Jadida city, seismic scenarios and tsunami generations.

3.1. Tsunami simulation

To evaluate the impact of a future tsunami event on El-Jadida city, three tsunamigenic faults were considered as potential sources (Table.1) (Blanc 2009). The Gorringe Bank Fault, the Marquês do Pombal Fault, and the Horseshoe Fault (see section 2.1). These faults are submarine structures located offshore in the Gulf of Cadiz, a region known for its seismotectonic activity (Hayward et al. 1999; Zitellini et al. 2001; Gràcia et al. 2003; Cunha et al. 2010), its seismo-stratigraphic signature (e.g. Bartolome et al. 2012; Martínez-Loriente et al. 2018), and an abundance of instrumental seismic data (ISC2020).

To model potential tsunamis waves generated by these faults, we used MIRONE simulation software (Luis 2007), which employs the Mansinha equation (Mansinha and Smylie 1971) to generate these waves (using the elastic deformation tools), and the TINTOL code to simulate their propagation in the Gulf of Cadiz as well as their inundation impact along the El-Jadida coastline. A rectangle, based on fault lengths and length/width ratios, was used to simplify the geometry of the faults and to fix the slip amplitude accordingly (Scholz 1981). Using

the faults parameters, the magnitude for each earthquake scenario (Table. 1) is automatically computed by the numerical simulation software. The equation is the seismic moment's formula (Eq.1 and Eq.2) (Aki 1966):

$$M_o = \mu \times A \times D \quad (1)$$

Where D is coseismic displacement, A is the rupture area (km²) and μ is the crustal rigidity coefficient (Nm⁻²). To the magnitude of the event, MIRONE adopts the M_o - M_w equation (Hanks and Kanamori 1979):

$$\text{Log}_{10} (M_o) = 1.5 \times M_w + 9.05 \quad (2)$$

Where M_o is the seismic moment (Nm) and M_w the moment magnitude.

The bathymetric/topographic data used for this simulation were downloaded from the GEBCO database (General Bathymetric Chart of the Oceans, https://www.gebco.net/data_and_products/gridded_bathymetry_data/ , accessed December 2019). The computation was performed using 0.8s time steps for a total duration of 6120s. This dataset is nested for consecutive calculations of tsunami generation and propagation in an open boundary condition as well as inland inundation.

The MIRONE software uses a nested grid system with different grid resolutions in order to generate tsunami simulations at various spatial resolutions. The main grid has a 300m-resolution and was used for tsunami propagation in the Gulf of Cadiz. The second grid, improved by transplanting the main grid using 'transplant 2nd grid tool' (Luis 2007), has a 60m-resolution and was used for inland inundation at El-Jadida. The outputs of the simulations are raster maps of the flooded areas featuring the maximum wave height for each pixel (see section 4.1).

Table 1: Active fault parameters used to simulate tsunamigenic scenarios in the Gulf of Cadiz (modified from Omira et al. 2009). L: the length of the fault; W: the width of the fault; μ : the crustal rigidity and M_w : the moment magnitude.

	Dimension (km)		Fault parameters						
	L	W	Depth	Slip	Strike	Dip	Rake	$\mu (\times 10^{10} \text{Nm}^{-2})$	M_w
Source			(km)	(m)	($^{\circ}$)	($^{\circ}$)	($^{\circ}$)		
Gorringe Bank Fault	127	60	5	8.3	233	35	90	3.0	8.2
Marquês do Pombal Fault	129	70	4	8	20	35	90	3.0	8.2
Horseshoe Fault	165	70	4	10.7	42.1	35	90	3.0	8.4

3.2. Quantitative Risk Assessment (QRA)

Although three scenarios were used for the simulation, only the one with the Horseshoe Fault defined as the source was retained for QRA (Table.1). This scenario was chosen because this fault has been responsible for many events of significance in recent years (Pro et al. 2013), and it was linked in many studies to the 1755 tsunamigenic earthquake (Fig.1-A) (e.g. Solares and Arroyo 2004). In addition, this scenario is also expected to produce the biggest waves (e.g. Omira et al. 2009).

To perform the QRA calculations, the equations system from Fell et al. (2005) was used since it takes into consideration both the natural hazard aspects and the socio-economic characteristics of a given area. This set of equations allows calculating two types of risk: the annual risk of loss of property and the annual risk of loss of life.

3.2.1. Annual risk of loss of property

Eq. 3 allows to calculate the annual risk of loss of property (R_p) caused by a potential natural hazard (in our case a tsunami event).

$$R_p = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V \times E \quad (3)$$

To calculate R_p using equation (3), the annual probability of the tsunami event $P_{(H)}$, the probability of its spatial impact given the hazardous event $P_{(S:H)}$, the probability of the element at risk being present along the path of the

flood $P_{(T:S)}$, the vulnerability of the exposed elements “V” and the estimated value of the property E must be individually calculated.

In the Gulf of Cadiz, tsunamigenic earthquakes have mean recurrence period of 1000 years (Gutscher et al. 2006), yielding an annual probability ($P_{(H)}$) of 0.001. In the absence of an existing early warning center against tsunamis (Birouk et al. 2020), we estimated that constructions, businesses and other assets couldn’t be relocated away from the risk area, which means that temporal probability of the consequence occurring is $P_{(T:S)}=1$. As for $P_{(S:H)}$, the lack of a numerical estimation of the simulation results accuracy, means that its calculation could not be objectively accomplished. However, we considered that the probability of spatial impact for all elements reached by the flood is $P_{(S:H)}=1$, since reinforced-concrete buildings and all assets in the area cannot be displaced in a short period of time.

To calculate the vulnerability of constructions to tsunamis, all buildings in the city were grouped into homogenous residential blocks, which were then classified into five categories (A, B, C, D and E), following in Atillah et al. (2011). This classification system was chosen because the building types and practices in El-Jadida city and those of the areas investigated by these authors are similar. Therefore, the estimation of their vulnerability can be achieved using the damage functions proposed by Gardi et al. (2009) (Fig. 6). To adapt this model to the numerical input data format needed for equation (3), vulnerability classes presented in figure 6 were converted to percentages (D0 = 0% damage, D1 = 20%; damage, D2 = 40%, D3 = 60%, D4 = 80%, and D5 = 100%) while the mean wave elevation for each block was derived from the simulation results. The obtained (V) value was then attached to each individual block of buildings of the same type. The last input variable needed to calculate $R(p)$ using equation (3) is the material value of the exposed buildings (E), which was obtained by multiplying the reference unit-price for each square meter acquired from the real estate price assessment report (D.G.I. 2015), by the total surface of each impacted residential block.

In addition to buildings, the road network is also a very important asset that must be included in R_p estimations. In El-Jadida city, paved roads/streets are 243 km long. The unit price used in this study is 216\$ per km which is a reasonable estimation of road cost in developing countries including Morocco (Collier et al. 2016). For quantifying vulnerability of roads, a reference value of 60 % is used (Ginkel et al. 2021).

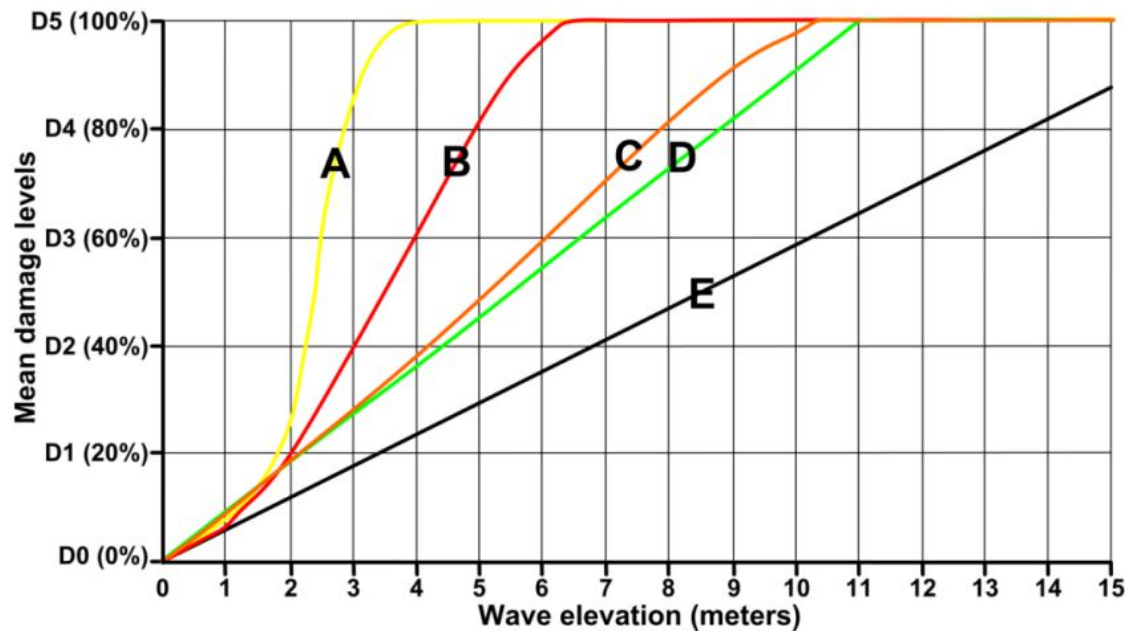


Figure 6: Damage functions for building classes A, B, C, D and E derived from experimental data from the area southwest of Banda Aceh (Sumatra, Indonesia) by GSC (modified after Gardi et al. 2009).

3.2.2. Annual risk of loss of life

Similarly to the annual risk of loss of property, the risk of loss of life $R_{(LoL)}$ can be estimated using the following equation:

$$R_{(LoL)} = P_H \times P_{(S:H)} \times P_{(T:S)} \times V \quad (4)$$

with the only difference being the mobility of the issues at stake and the equations system used for calculating their vulnerability. Hence, $P_{(T:S)}$ and V values are different from those used in equation (3). It is also important to note that the E value equals to 1 since the risk is calculated for each individual.

For calculating $P_{(T:S)}$, the concept of evacuation time t_e is adopted, which measures the time needed for a person to reach safe ground. This is important for estimating the number of people exposed to the tsunami wave. To quantify t_e , we used Eq.5, according to which evacuation time mainly depends on the distance from coast to safe ground (x_{max}), the distance from the coast to a person's location (x_0), the person's evacuation speed (c) and the time lapse between the tsunami occurrence and the beginning of evacuation (t_d) (Okumura et al.2017).

$$t_e = \frac{x_{max}-x_0}{c_e} + t_d \quad (5)$$

While x_{\max} and x_0 can be automatically measured using a geographic information system (GIS) software, for inhabitants of each individual residential block, the evacuation c_e speed cannot be measured in the study area due to the absence of recent past events. For this reason, values estimated by Carey (2005) and adopted by Okumura et al. (2017) to perform QRA on the 2011 Okahura tsunami are also used in this study (Table.2). To adapt these reference values to the demography of El-Jadida, true population age percentage are used (HCP 2014) (Table.2).

In this respect, we propose the following Eq.6 to estimate $P_{(T:S)}$

$$P_{(T:S)} = \frac{P_N + P_D}{2} \quad (6)$$

Where P_N is the probability of escaping the tsunami provided it occurred at night, and P_D is the same probability for a tsunami occurring during daytime. In the absence of an alarm system at the area (Birouk et al. 2020), we estimate that P_N is equal to 1 since most of the population will be inactive. For P_D values, a binary outcome is expected where persons able to escape the tsunami wave have a value of 0 and those unable to escape a value of 1. To determine which zones are safe and which ones are not, we used the evacuation model proposed by Okumura et al. (2017).

However, not all persons exposed to the tsunami flood would be killed as demonstrated during the 2004 Asian tsunami, where a significant portion of the population survived the event. Accordingly, the V value depends on the probability of loss of life F_D , which could be estimated using equation 7 (CDMC 2003; Jonkman et al. 2008), with the only variable being the wave height (h) at the affected area:

$$F_D = 0.0282e^{0.2328h} \quad F_D \leq 1 \quad (7)$$

Table 2: Evacuation speed and percentage of age categories in El-Jadida city

	Age distribution	Percentage of population	Evacuation speed (m/s)
Children	0-14	25,5	1.2
Average adult	15-64	69,8	1.38
Old/disabled	>65	4,7	1

4. Results

4.1. Tsunami waves propagation along the Moroccan Atlantic coast.

The tsunami simulations generated by MIRONE (Fig. 7) show that depending on the user provided fault parameters used to define the source area, the maximum and minimum wave heights can vary significantly from one model to the other (Fig. 7). Although studying the wave propagation along the whole length of the Moroccan coast enables a better understanding of the near-field and far-field effects of the bathymetry on its mechanisms, our description of the obtained results will essentially focus on the most important cities in this area.

In the first scenario, where the Horseshoe Fault is set as the tsunamigenic source, the maximum wave height values range from 11 m to 27 m (Fig. 7). The highest waves would be recorded in Rabat, reaching up to 27 m in the southern part of the city. To the north, the wave height would progressively decrease with values ranging from 11 to 15 m. On the other hand, the lowest wave height would be recorded (11 to 12 m) in Casablanca and its surrounding areas. To the south, waves arriving at the shoreline would reach heights of 20m or more.

In the second and least severe scenario (Marquês do Pombal Fault) (Fig.8-B), the maximum wave height values range from 4 m to 11 m, with areas located in the north (Tangier and Larache) receiving the highest tsunami waves (>8m). South of Casablanca, waves with heights reaching up to 9 m are also expected, while in Rabat waves may reach roughly 4m.

The last scenario (Gorringe Bank Fault) (Fig.8-C) yields a wide range of wave height values with a maximum and minimum of 24 m and 4 m respectively. However, the simulation stops before the leading propagating wave reaches the center and northern segments of the shoreline. Reasons for this are discussed in section 5.1. In the southern part of the study area, where the wave reaches the coast of El-Jadida city, the water elevation height would attain 24 m. In other parts where the tsunami does not reach the coast, the wave heights are estimated to be: **(1)** at least 6 m off the northern coasts, including Rabat; and **(2)** at least 9 m in Casablanca and the neighboring coasts.

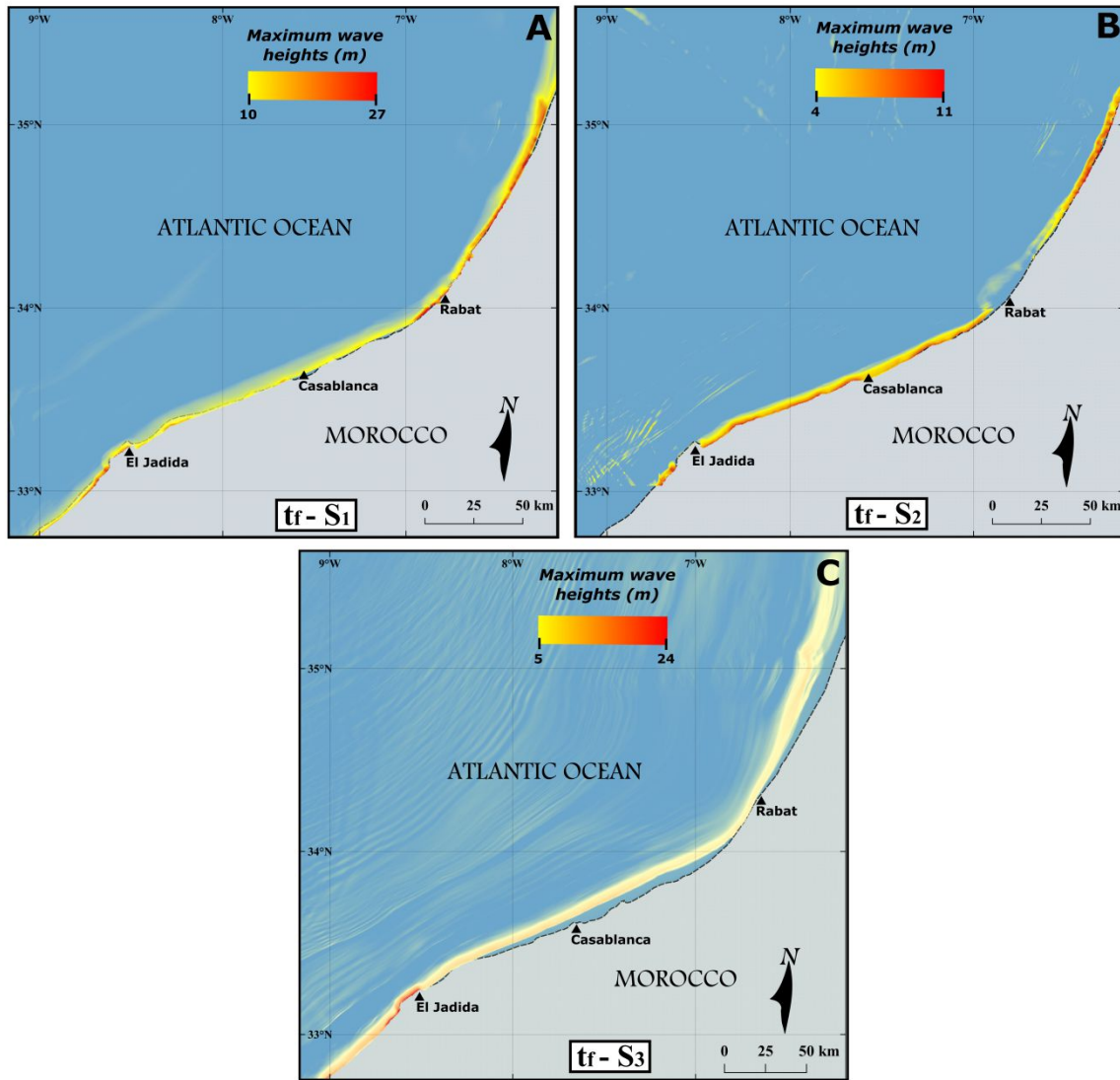


Figure 7: Maximum water elevation caused by the most credible earthquake scenarios in the Gulf of Cadiz region. A: Result of Horseshoe Fault scenario; B: Result of Marquês do Pombal Fault scenario; C: Result of Gorringe Bank Fault scenario. tf: final time for tsunami simulation; S: Scenario.

From the results obtained by this set of simulations, the Horseshoe Fault scenario produced the highest series of waves. For this reason, and because other authors (e.g. Pro et al. 2013; Buform et al. 2020) also consider it to be the most likely source for the 1755 event, it was used for QRA. A zoom on El Jadida city allows examining the tsunami run-up variation at the city-scale (Fig. 8).

4.2. Building damage and human loss estimations for El-Jadida

The QRA results show that most districts of El-Jadida city are highly exposed to tsunami risk (Fig. 8 and Table. 3). For the districts of Saada, Sidi Bouzid, Al Amal, Kaala and Al Jawhara/Sidi Moussa, the R_p is in excess of one million dollars a year, which represents a very high economic cost to the population, especially when considering the fragile socio-economic setting of El-Jadida city and that of Morocco in general (H.D.R. 2020). At the city scale, the (R_p) amounts to more than 14M\$/yr, which constitutes a considerable risk to the economic development of the city. Most of the elements at risk are buildings since the value of roads is found to be low in comparison to other assets (31 k\$/yr). However these values of risk are only low because the return period of the tsunami is very long, since one event could cost more than 14 B\$ only including direct damages.

Although the assessment of economic risk is of importance, the R_{LOL} is the most crucial value to evaluate, especially in the case of rapid onset, large-scale natural hazards such as tsunamis, which could claim hundreds of thousands of lives in a matter of minutes. In the study area, the projection of residential bloc locations (where most of the population is found) on the evacuation model (Fig.9) shows that 46% of the inundated zone can safely evacuate if the tsunami were to occur in daytime and the evacuation were to start 60 min after the triggering of tsunami waves or earlier. However, it is important to note that distances used for the projection of residential blocs location relative to safe ground are calculated using the Manhattan approach. This accounts for delays related to the geometry of buildings and the complexity of El-Jadida's road network. In the districts of Bir Anzaran, Saada, Sidi Bouzid, Al Amal, Lala Zohra and El Jawhara/Sidi Moussa, R_{LOL} values exceed 10 lives/yr. Although such values seem negligible when compared to the total number of residents in each district, it is important to note that the temporal hazard of the simulated event is very low (0.1%). Thus, in the case of a tsunami-generating earthquake like that of 1755, more than 34 000 (Table. 3) people could lose their lives.

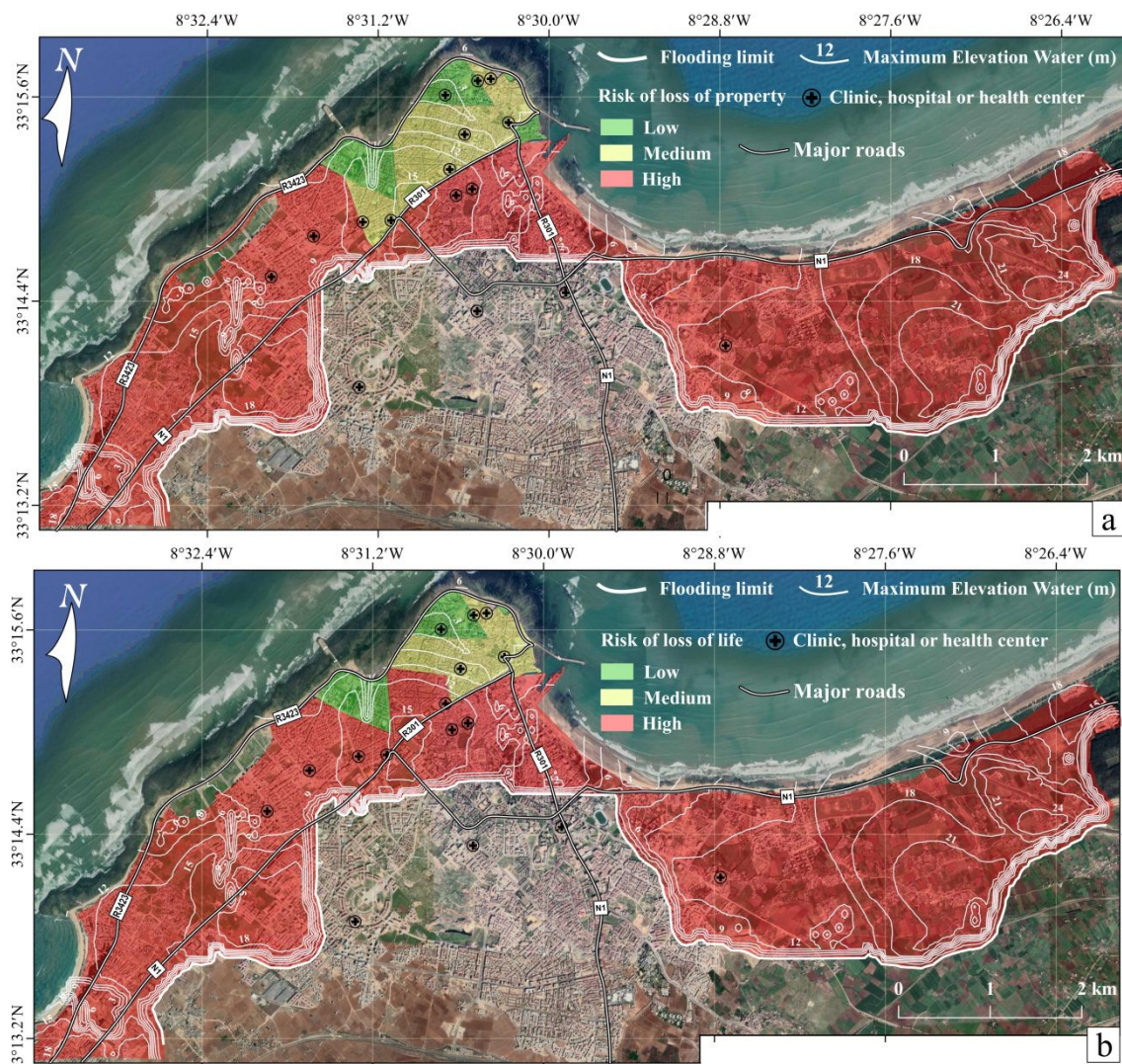


Figure 8: Quantitative Risk estimation maps for El-Jadida city (source of background image: Google map (<https://maps.google.com>) integrated in QGIS software as Basemap). **a.** R_p map. **b.** R_{LOL} map.

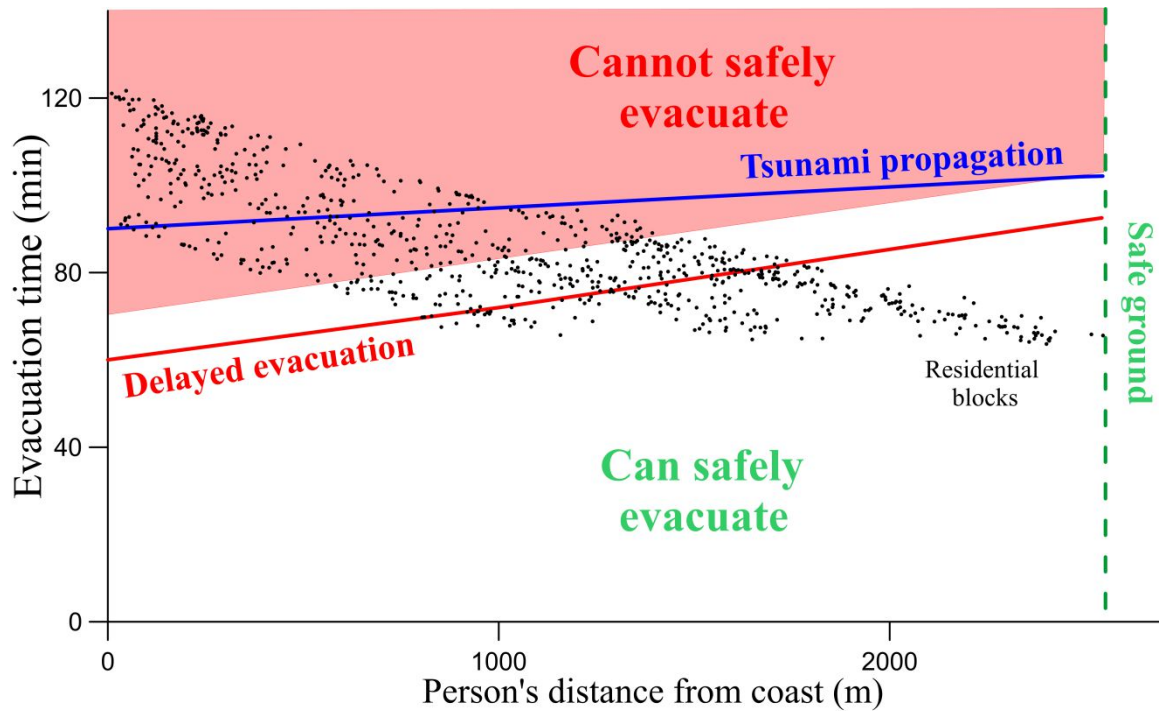


Figure 9: Projection of residential block locations and evacuation time on the Okumura et al. (2017) evacuation model. The black dots "represent vital infrastructure that is deemed essential to the rescue and evacuation operations".

Table 3: Quantitative risk estimation result for El-Jadida city. Red : high risk. Yellow: medium risk. Green: low risk.

District	Issues at stake (M\$)	Risk of loss of property (M\$/yr)	Issues at stake (Lives)	Risk of loss of life (Lives/yr)
<i>Sidi Daoui</i>	770.50	0.43	1536	0.15
<i>Mazagan</i>	2.29	0.00	687	0.09
<i>Mouilha</i>	-	-	-	-
<i>Biranzaran</i>	822.19	0.56	4392	2.08
<i>Saada</i>	2102.19	1.03	19670	3.85
<i>Sidi Bouzid</i>	1856.98	1.47	13155	7.08
<i>Amal</i>	2270.71	1.93	17938	4.21
<i>Salam</i>	-	-	-	-
<i>Derb Al Hajar</i>	4.53	0.09	2855	0.34
<i>Lala Zahra</i>	176.36	0.18	3844	2.31
<i>Derb Ghalef</i>	577.25	0.36	2118	0.29
<i>Kasr Lahmar</i>	3.94	0.00	-	-
<i>Kaala</i>	2381.14	1.86	16643	4.22
<i>El Kods</i>	-	-	-	-
<i>El Jawhara / Sidi Moussa (z)</i>	8546.49	6.54	26083	9.55

Road network/Streets	52.54	0.03	-	-
El Jadida	18744.07	14.48	108926	34.17

5. Discussion

5.1. Limitations of the tsunami simulation

Despite the data enhancement performed through several iterations in the MIRONE software, the relative low resolution the GEBCO bathymetric/topographic data (300m) constitutes a limitation, especially when used for city-scale hazard mapping. Therefore, the areas affected by the simulated tsunami could be off by dozens of meters horizontally due to the simulation model dependence upon near source and regional bathymetry. Hence, several artifacts related to over-shoots in the data, in areas of relatively steep topography (www.gebco.net) could negatively impact the accuracy of the results. Also, small sub-marine canyons and manmade coastal structures (port protection structures), which govern the form, amplitude, breaking wave points and the energy of the tsunami, could be undetected because of the low-resolution of the input data. However, according to sub-marine canyon maps of Morocco presented by Wynn et al. (2000), no small canyons, deep enough to be considered, exist between the source area and El-Jadida city. Consequently, their effect on the results is deemed negligible at best.

It is also important to note that parameters of active faults used to define the source areas for our simulations, are based on investigations conducted on the 1755 event and recent earthquakes, in the Gulf of Cadiz (e.g., Johnston 1996; Hayward et al. 1999; Zitellini et al. 2001; Silva et al. 2017). The reason we only used the Horseshoe, Gorringe Bank and Marquês do Pombal faults for our simulations is their high spatio-temporal seismic hazard, which has been demonstrated in many previous studies (Gutscher et al. 2006; Silva et al. 2017).

In addition, the inability of the simulation software to model wave propagation once tsunami travel time exceeds 6120s has proven to be a great challenge when the Gorringe Bank Fault was defined as the source for the tsunami generating earthquake (Fig.6-C). In our opinion, this is a significant limitation of this software especially when tsunamigenic earthquakes occur far from the coast. Nevertheless, MIRONE could still be considered a good tool for simulating near shore to medium range tsunami generating earthquake events, since results of simulations 1 and 2 (Fig.6-A and B) have proven to be similar to those obtained using commercial softwares (e.g. Omira et al., 2012).

Also, the magnitude calculated for the simulated event is in the order of 8.4, which is lower than values obtained by Leet et al., (1950) (8.75 – 9) as well as those calculated by Levret (1991), Baptista et al. (1998) and Gutscher et al. (2006) (8.5 – 9). However, recent efforts to estimate the magnitude of the 1755 event puts its value in a range of (7.2 – 8.2), which is the closest to results obtained using equations 1 and 2 (see section 3).

Another limitation of the software used in this study is the necessity of making simplifying assumptions about the source area's geometry and the number of fault segments responsible for the triggering event. Thus, we are unable to simulate complex seismic scenarios such as the one proposed by Fonseca (2020), which invokes the basal rupture of the Gulf of Cadiz accretionary prism as a cause for a seismic event in the Gulf of Cadiz. This constraint might have an impact on the magnitude values calculated by the simulation software, and thus the tsunami waves propagation and run-ups. However, we don't think that the difference will be significant enough to radically change the QRA results. In addition, even commercial, state of the art softwares are unable to model this type of scenario, which makes this not a software shortcoming, but rather a technical limitation needing to be overcome.

According to our results, the wave heights in El-Jadida exceed 15 m and the tsunami wave inundation distance reaches up to 1 km. These numbers are in agreement with historical testimonies (records) (Soyris 1755; El Mrabet 2005), which were thought to be exaggerated, as well as recent computer simulation models (Mellas et al. 2012). However, Omira et al. (2015) obtained different results. According to these authors and others (Omira et al. 2012), wave heights values in excess of 10 meters should be regarded as over-estimated and unrealistic. Despite this, we believe that an event of such proportions is possible since the old town of Mazagan, the elevation of which exceeds 6 m, was impacted by the 1755 event.

5.2. Reliability of the QRA method used in this study

Although the QRA method proposed by Fell et al. (2005) takes into consideration all aspects of a given risk, it is seldom used in tsunami studies (e.g. Li et al. 2021). Our results show that this system can yield interesting results, allowing the assessment of economic and societal damages caused by tsunami events as well. Nevertheless, one must note that because the exact location of the 1755 source area and its precise recurrence interval remain uncertain, the calculated R_p and R_{LOL} values for El-Jadida city suffer from inaccuracies that cannot be numerically quantified. Indeed, the recurrence period suggested by previous studies range from 300 to 2000 years (Ribeiro et al. 1996; Gutscher 2004; Ruiz et al. 2013), which means that the error if one extreme value or the other were used could be important. For this reason, an intermediate value of 1000 years was adopted in order to minimize the error and consequently avoid largely underestimating or overestimating the true

risk. In fact, this value is also at the low range of those generally agreed on regarding the current convergence rates recorded in the Gulf of Cadiz (1cm/yr) (Gutscher *et al.* 2006).

In addition to inaccuracies in the spatio-temporal parameters of the natural hazard, errors related to the simulated wave heights (discussed in section 5.1) influence the V value, which could, in some areas, lead to inaccurate QRA of the true impact on buildings. Since the spatial errors of the topographic/bathymetric data are difficult to quantify (www.gebco.net), their influence on the QRA results is consequently difficult to estimate. However, in most areas of El-Jadida city, we consider that wave height values are large enough for us to deem vertical errors in the input data irrelevant.

Moreover, one must stress the fact that this method only quantifies the value of property directly lost in consequence to the catastrophic event. Nevertheless, rebuild efforts and debris clean-up operations cost, as well as consequential damage to the regional economy of the area are not included in the QRA results. This is due to a lack of recent tsunami occurrences alongside the Moroccan Atlantic shoreline which could serve as reference points for the estimation. Despite the abundance of research elsewhere in the world, especially for the Japan 2011 tsunami (Ghaderi and Henderson 2013; Naito *et al.* 2014; Maximenko *et al.* 2018), the particularities of the Moroccan economy makes it difficult to compare the results for both areas. In consequence, we consider that a post-disaster rebuild and clean-up will cost as much as building a new city from scratch. To do so, the unit price for urban infrastructure construction given in hectares is estimated to be around 1,3M\$ (MAUH 2012) which accounts for a total of 16.9 M\$ for the affected area. For house reconstruction efforts, a unit price of 1000\$/m² (Triantafyllou *et al.* 2018) is adopted to estimate the cost of rebuilding houses at the affected districts of El-Jadida, which totals about 1.3 B\$.

Also, inaccuracies in R_{LOL} calculation using the Fell *et al.* (2005) method can result from the failure of this system to incorporate the role of critical infrastructures and rescue and recovery efforts in reducing the tsunami post-disaster impacts. For example it seems that most hospitals and care centers are located inside the flooded area (Fig.8) which means that the injured must be transported hundreds of kilometers before receiving the care they need. This constitutes a true logistical challenge for authorities, especially knowing that major road lines connecting the city to other urban areas (N1 and R301) will also be partially inundated by the tsunami waves (Fig.8). For this reason we propose constructing new healthcare centers in areas located away from high risk zones in order to avoid casualties induced by logistical problems. Regarding the evacuation routes, the density of urbanism and the non-regulated construction in many districts of the city constitute a true obstacle because of

socio-economic problems related to acquiring land property for the construction of such structures. In this regard, we believe that the best solution is to install an operational early warning system and to educate the population about the danger of tsunamis and the locations of safe zones if such events were to occur. Although the most intuitive idea to protect the population against tsunamis is to build coastal defense structures, one should consider the important height of tsunami waves at the area ($> 20\text{m}$) which is a true technical and economic challenge for the state. A better alternative will be the design of vertical evacuation structures in high risk areas in a way that allows the rapid evacuation of most people living in these districts. Ideas for the planning and design of such structures are proposed by Heintz and Robertson (2008); Park et al.(2012) and Wood et al. (2014).

Regarding the geographic distribution of high and low risk areas (Table. 3) (Fig.8), it seems that despite their closeness to the shoreline, many districts such as Mazagan, Mouilha, Salam, Kasr Lahmar and El Kods are low-risk. This is because these districts were built on the rocky Cape Mazagan, which acts as a natural barrier that dissipates the tsunami waves energy and thus decreases tsunami impact on the shore.

6. Conclusion

In the Gulf of Cadiz, Marquês do Pombal, Gorringe Bank and Horseshoe faults could trigger tsunamis in the future. According to our simulation results, out of the three the Horseshoe Fault could produce the largest tsunami. For this reason, and because of its relation to recent and old events of significance, this fault was picked as the most likely source of a potential tsunami. However, despite the differences between previous simulations and those performed in this study, the results obtained agree on the fact that the northern Atlantic coast of Morocco is highly exposed to the tsunami hazard, which could impact areas with high population densities and economic interests.

For El-Jadida city, QRA results show that such events could be disastrous especially in the districts of Saada, Sidi Bouzid, Amal, Kaala and El Jawhara / Sidi Moussa, which are thus very high-risk areas. On the other hand, and despite its closeness to the shoreline, the Mazagan district, built on a low-elevation rocky cape might be less affected. Based on these results, we recommend establishing a tsunami response and mitigation strategy that, should allow for a quicker and more accurate intervention in the case of a future extreme event. The basis of such a strategy must include but not be limited to the installation of an effective early response system, the

479 education of the coastal population about the dangers of tsunamis and the most exposed areas and the
480 construction (if possible) of vertical tsunami evacuation structures.

481 **Highlights**

- 482 - Multi-assessment of the impacts of tsunami along the northern Atlantic coast of Morocco.
- 483 - Quantitative Risk Assessment to calculate the loss of property and life in El-Jadida city.

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491 **Declaration of competing Interest**

492 The authors declare that they do not have any personal relationships or financial interests that influence the work
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