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Abdelkarim Tadibaght, Kamal Agharroud, Ali Bounab, Abdelmounim El M'rini, Lionel Siame, Younes El Kharim, Olivier Bellier, Otman El Ouaty

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

4 Abdelkarim Tadibaght<sup>1\*</sup>, Kamal Agharroud<sup>2</sup>, Ali Bounab<sup>2</sup>, Abdelmounim El M'rini<sup>1</sup>, Lionel Siame<sup>3</sup>, Younes El  
5 Kharim<sup>2</sup>, Olivier Bellier<sup>3,4</sup>, Otman El Ouaty<sup>1</sup>

6 <sup>1</sup> LR3G, FS, Abdelmalek Essaadi University, Tétouan, Morocco

7 <sup>2</sup> GERN, FS, Abdelmalek Essaadi University, Tétouan, Morocco

8 <sup>3</sup> Aix Marseille Univ, CNRS, IRD, INRAE, Coll France, CEREGE, Aix-en-Provence, France

9 <sup>4</sup> Aix Marseille Univ, CNRS, ECCOREV, Aix-en-Provence, France

10 \* Address correspondence to Abdelkarim Tadibaght

11 E-mail: [tadibaghtabde@gmail.com](mailto:tadibaghtabde@gmail.com)/Tel: +212657966260/Orcid: <https://orcid.org/0000-0001-7161-0154>

12 Kamal Agharroud Orcid: <https://orcid.org/0000-0002-2079-4245>

13 Ali Bounab Orcid: <https://orcid.org/0000-0002-3411-3930>

14 Abdelmounim El M'rini Orcid: <https://orcid.org/0000-0002-7963-5660>

15 Lionel Siame Orcid: <https://orcid.org/0000-0002-4288-9528>

16 Younes El Kharim Orcid: <https://orcid.org/0000-0001-9451-3955>

17 Olivier Bellier Orcid: <https://orcid.org/0000-0002-3213-7306>

18 Otman El Ouaty Orcid: <https://orcid.org/0000-0003-0593-4358>

19           **Abstract**

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

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

34           **1. Introduction**

35           Tsunami is one of the deadliest natural hazards, claiming hundreds of thousands of lives all around the  
36 world (e.g., Bernard *et al.* 1988; Doocy *et al.* 2007). In addition, tsunami events also constitute a great risk to  
37 coastal regions increasingly impacted by different human activities. For instance, the tsunami of December 26<sup>th</sup>  
38 2004 killed more than 300 000 people and caused economic damage exceeding \$10 billion to countries  
39 surrounding the Indian Ocean (Sharpley 2005). This disaster has spurred scientific research with aim of better  
40 understanding tsunamis and their potential economic, environmental and societal impacts.

41           In the Gulf of Cadiz (Fig.1), with the exception of some small tsunami waves generated by the 1969 earthquake  
42 (Baptista *et al.* 1992), no tsunami events were experienced during course of the twentieth century. However, the  
43 massive destruction caused by tsunami waves associated with the historical 1755 Lisbon earthquake (Levret  
44 1991), strongly highlights the exposure of the this region to this hazard and its proneness to produce catastrophic  
45 events in the future (Baptista *et al.* 1998; Gutscher *et al.* 2006).

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

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

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

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

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

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

## 86 **2. Study area :**

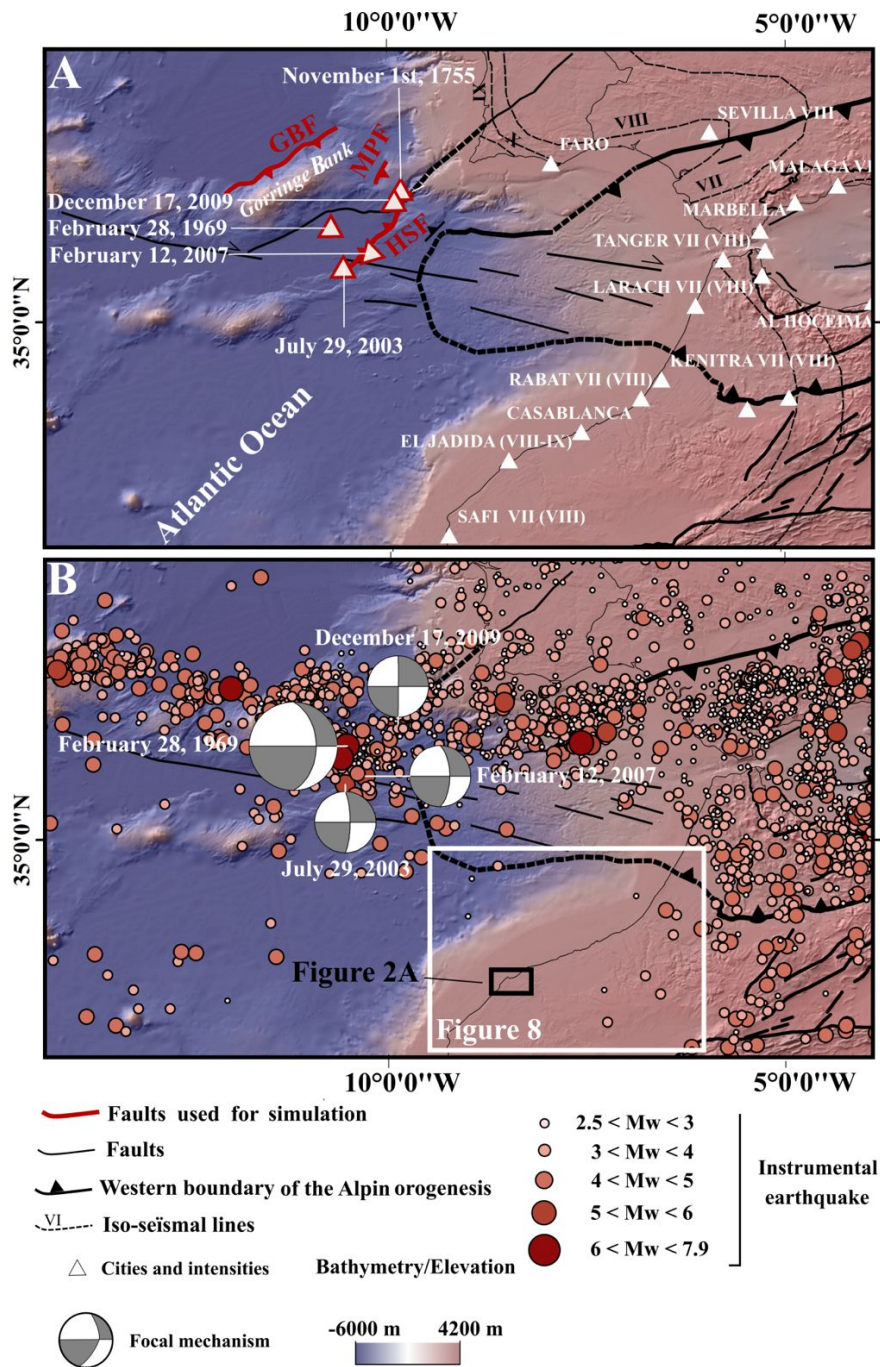
### 87 **2.1. Seismic setting and tsunamigenic faults in the Gulf of Cadiz.**

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

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

102 The locations of some of the recent earthquake epicenters can be determined with more accuracy (Fig. 1).  
103 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; Buform 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, Buform 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.



117

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

## 125            **2.2. Tsunamis in Morocco**

126            Morocco is vulnerable to coastal hazards because its most economically influential cities are located  
127 alongside its Atlantic and Mediterranean shorelines. In addition to storms, coastal erosion, and sea level rise,  
128 tsunamis constitute the most dangerous coastal hazard threatening these newly-constructed human settlements in  
129 the area (Blanc 2009; Omira *et al.* 2010; Atillah *et al.* 2011; Renou *et al.* 2011). In fact, the impact of past  
130 occurrences, such as that of 1755, have been documented in old towns that have now grown into big cities close  
131 to, or on, the Atlantic shoreline (El Mrabet 2005; Blanc 2009). Several attempts to model the effects of these  
132 events and to estimate the risk to human life and goods, show that the region is widely exposed if similar events  
133 were to recur (Omira *et al.* 2010; Atillah *et al.* 2011; Renou *et al.* 2011; Mellas *et al.* 2012; Moussaoui *et al.*  
134 2017; Ramalho *et al.* 2018). In addition to historical documents, material evidence (geomorphic and sedimentary  
135 indices) for tsunamis or high energy events in Morocco have been found in many sites alongside the Moroccan  
136 Atlantic coast: (1) in Larache and Rabat (Medina *et al.* 2011), (2) Tahadart estuary (Talibi *et al.* 2016; Khalfaoui  
137 *et al.* 2020) and (3) close to the Loukkos river mouth, (Mhammdi and Medina, 2015). According to Soyris  
138 (1755), the Lisbon earthquake of 1755, the intensity of which reached VIII-XI on the Mercali scale, produced a  
139 large tsunami wave that affected northern Morocco, with El-Jadida city being one of the most impacted (Levret  
140 1991). Other descriptive data, as well as tsunami hazard assessments performed using simulations agree on the  
141 great impact of this event on El-Jadida city (e.g. Blanc 2009; Ramalho *et al.* 2018).

## 142            **2.3. Socio-economic setting of El-Jadida**

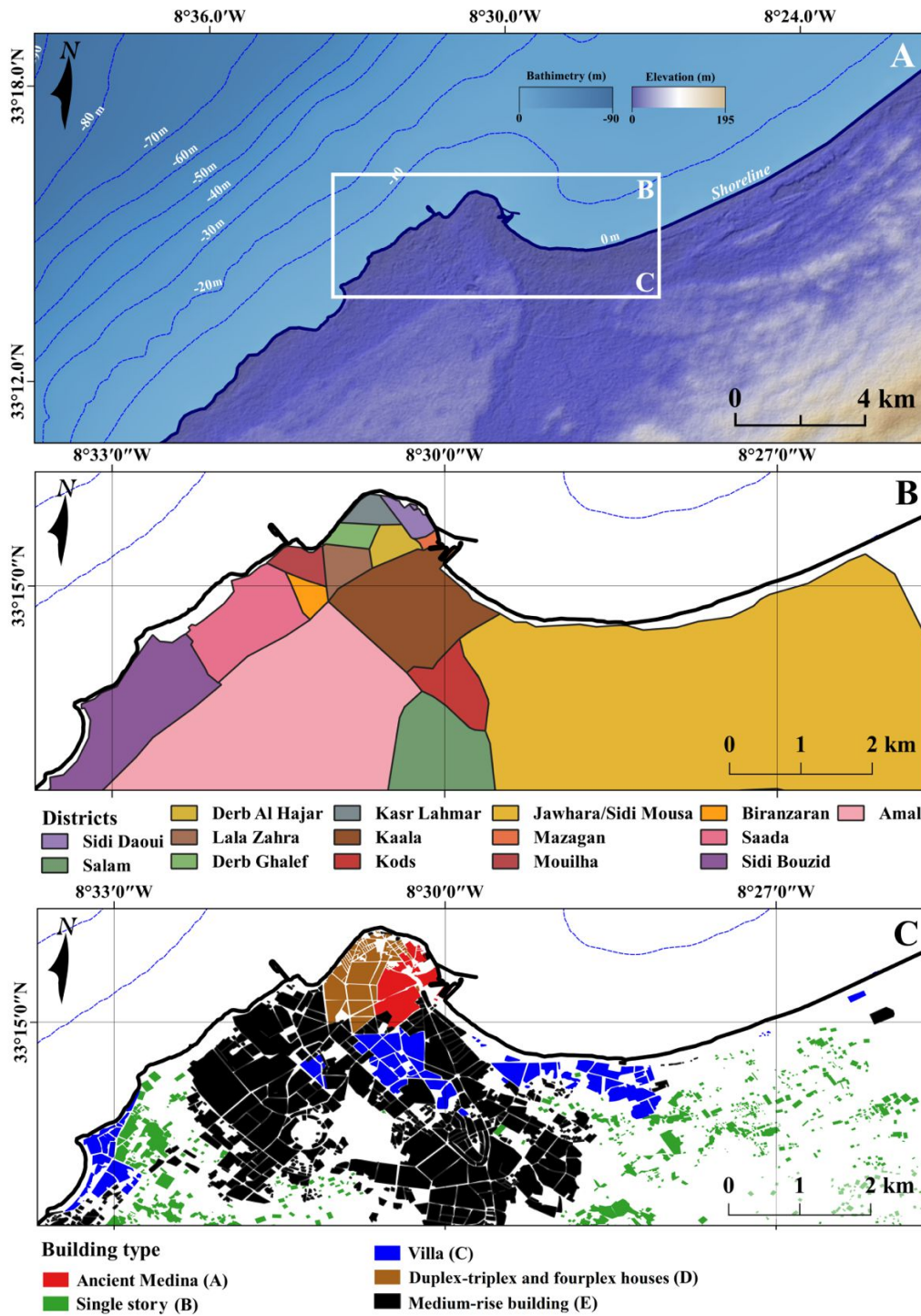
143            The largest and most important cities for the Moroccan economy (nearly 66% of its total Gross  
144 Domestic Product (GDP)) are located along its Atlantic coast (D.A.T. 2017). As such, any tsunami should have a  
145 long-lasting catastrophic impact on the economy of the country. Nevertheless,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

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



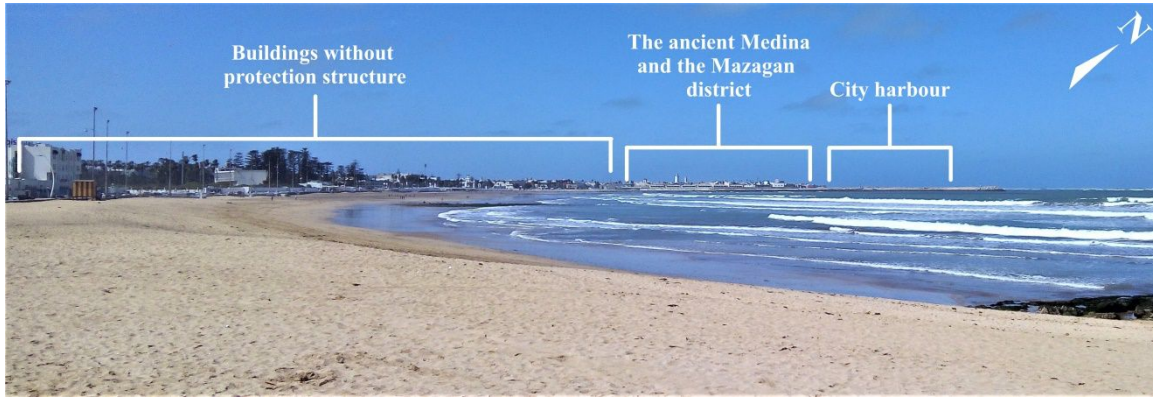
154 the international education standard, 23.3 % being illiterate (H.C.P. 2014); (4) the relatively high percentage of  
155 residents aged 55 or older (13% of El-Jadida's, i.e. for 25,000 people (H.C.P. 2014); (5) and the fact that most of  
156 El-Jadida's buildings are located within 3 km from the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



171

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

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

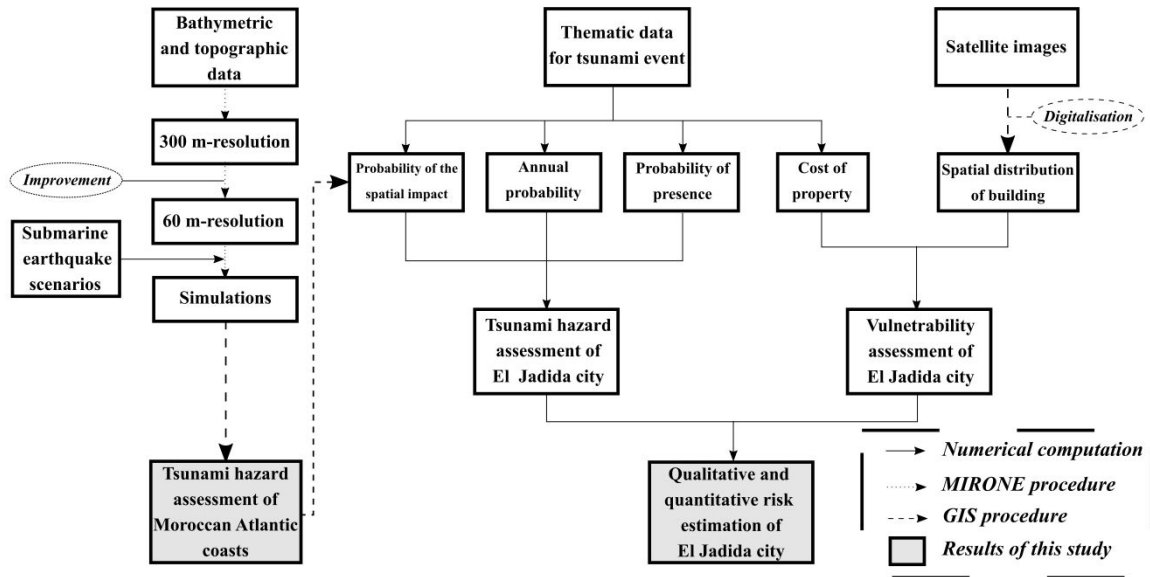


178

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

182 **3. Material and Methods**

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



185  
 186 Figure 5: Logical approach adopted to evaluate the tsunami risk in El-Jadida city, seismic scenarios and tsunami  
 187 generations.

188 **3.1. Tsunami simulation**

189 To evaluate the impact of a future tsunami event on El-Jadida city, three tsunamigenic faults were  
 190 considered as potential sources (Table.1) (Blanc 2009). The Gorringe Bank Fault, the Marquês do Pombal Fault,  
 191 and the Horseshoe Fault (see section 2.1). These faults are submarine structures located offshore in the Gulf of  
 192 Cadiz, a region known for its seismotectonic activity (Hayward et al. 1999; Zitellini et al. 2001; Gràcia et al.  
 193 2003; Cunha et al. 2010), its seismo-stratigraphic signature (e.g. Bartolome et al. 2012; Martínez-Loriente et al.  
 194 2018), and an abundance of instrumental seismic data (ISC2020).

195 To model potential tsunamis waves generated by these faults, we used MIRONE simulation software (Luis  
 196 2007), which employs the Mansinha equation (Mansinha and Smylie 1971) to generate these waves (using the  
 197 elastic deformation tools), and the TINTOL code to simulate their propagation in the Gulf of Cadiz as well as  
 198 their inundation impact along the El-Jadida coastline. A rectangle, based on fault lengths and length/width ratios,  
 199 was used to simplify the geometry of the faults and to fix the slip amplitude accordingly (Scholz 1981). Using

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

$$202 \quad M_0 = \mu \times A \times D \quad (1)$$

203 Where D is coseismic displacement, A is the rupture area (km<sup>2</sup>) and  $\mu$  is the crustal rigidity coefficient (Nm<sup>-2</sup>).  
204 To the magnitude of the event, MIRONE adopts the M<sub>0</sub>-M<sub>w</sub> equation (Hanks and Kanamori 1979):

$$205 \quad \text{Log}_{10} (M_0) = 1.5 \times M_w + 9.05 \quad (2)$$

206 Where M<sub>0</sub> is the seismic moment (Nm) and M<sub>w</sub> the moment magnitude.

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

212 The MIRONE software uses a nested grid system with different grid resolutions in order to generate tsunami  
213 simulations at various spatial resolutions. The main grid has a 300m-resolution and was used for tsunami  
214 propagation in the Gulf of Cadiz. The second grid, improved by transplanting the main grid using 'transplant 2nd  
215 grid tool'(Luis 2007), has a 60m-resolution and was used for inland inundation at El-Jadida. The outputs of the  
216 simulations are raster maps of the flooded areas featuring the maximum wave height for each pixel (see section  
217 4.1).

218

219

220

221

222

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

	Dimension (km)		Fault parameters						
	L	W	Depth (km)	Slip (m)	Strike (°)	Dip (°)	Rake (°)	$\mu$ ( $\times 10^{10} \text{Nm}^{-2}$ )	$M_w$
Source									
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

226

### 227 **3.2. Quantitative Risk Assessment (QRA)**

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

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

#### 237 **3.2.1. Annual risk of loss of property**

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

$$240 \quad R_p = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V \times E \quad (3)$$

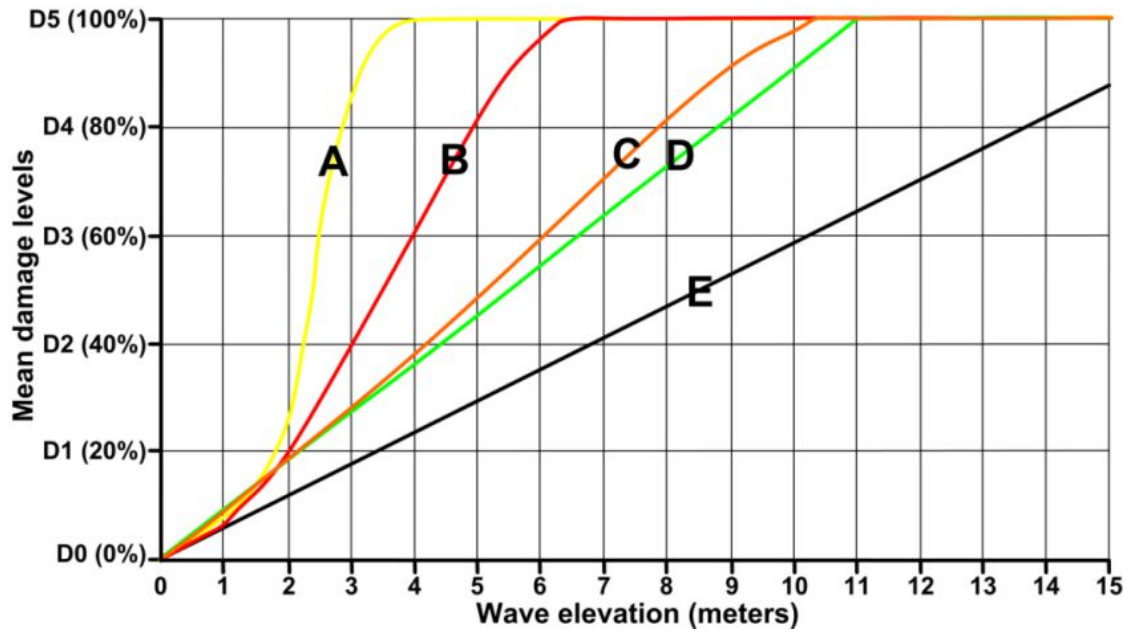
241 To calculate  $R_p$  using equation (3), the annual probability of the tsunami event  $P_{(H)}$ , the probability of its spatial  
 242 impact given the hazardous event  $P_{(S:H)}$ , the probability of the element at risk being present along the path of the

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

245 In the Gulf of Cadiz, tsunamigenic earthquakes have mean recurrence period of 1000 years (Gutscher et al.  
246 2006), yielding an annual probability ( $P_{(H)}$ ) of 0.001. In the absence of an existing early warning center against  
247 tsunamis (Birouk et al. 2020), we estimated that constructions, businesses and other assets couldn't be relocated  
248 away from the risk area, which means that temporal probability of the consequence occurring is  $P_{(T,S)}=1$ . As for  
249  $P_{(S,H)}$ , the lack of a numerical estimation of the simulation results accuracy, means that its calculation could not  
250 be objectively accomplished. However, we considered that the probability of spatial impact for all elements  
251 reached by the flood is  $P_{(S,H)}=1$ , since reinforced-concrete buildings and all assets in the area cannot be displaced  
252 in a short period of time.

253 To calculate the vulnerability of constructions to tsunamis, all buildings in the city were grouped into  
254 homogenous residential blocks, which were then classified into five categories (A, B, C, D and E), following in  
255 Atillah et al. (2011). This classification system was chosen because the building types and practices in El-Jadida  
256 city and those of the areas investigated by these authors are similar. Therefore, the estimation of their  
257 vulnerability can be achieved using the damage functions proposed by Gardi et al. (2009) (Fig. 6). To adapt this  
258 model to the numerical input data format needed for equation (3), vulnerability classes presented in figure 6 were  
259 converted to percentages (D0 = 0% damage, D1 = 20%; damage, D2 = 40%, D3 = 60%, D4 = 80%, and D5 =  
260 100%) while the mean wave elevation for each block was derived from the simulation results. The obtained (V)  
261 value was then attached to each individual block of buildings of the same type. The last input variable needed to  
262 calculate  $R(p)$  using equation (3) is the material value of the exposed buildings (E), which was obtained by  
263 multiplying the reference unit-price for each square meter acquired from the real estate price assessment report  
264 (D.G.I. 2015), by the total surface of each impacted residential block.

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



269

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

272 **3.2.2. Annual risk of loss of life**

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

275 
$$R_{(LoL)} = P_H \times P_{(S:H)} \times P_{(T:S)} \times V \quad (4)$$

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

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

284 
$$t_e = \frac{x_{max} - x_0}{c_e} + t_d \quad (5)$$



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

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

$$291 \quad P_{(T:S)} = \frac{P_N + P_D}{2} \quad (6)$$

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

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

$$302 \quad F_D = 0.0282e^{0.2328h} \quad F_D \leq 1 \quad (7)$$

303 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

304

## 305 4. Results

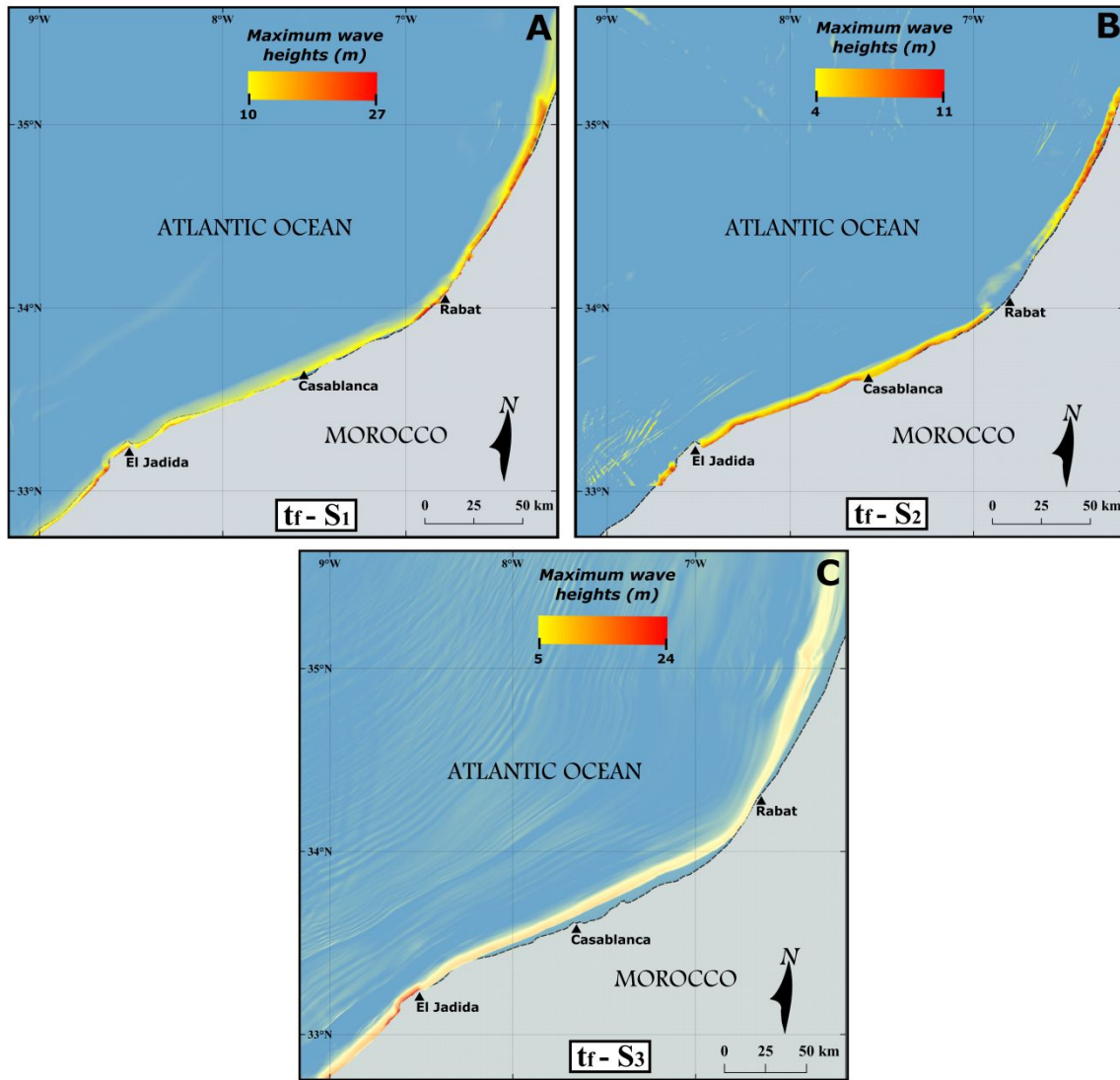
### 306 4.1. Tsunami waves propagation along the Moroccan Atlantic coast.

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

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

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

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



328

329

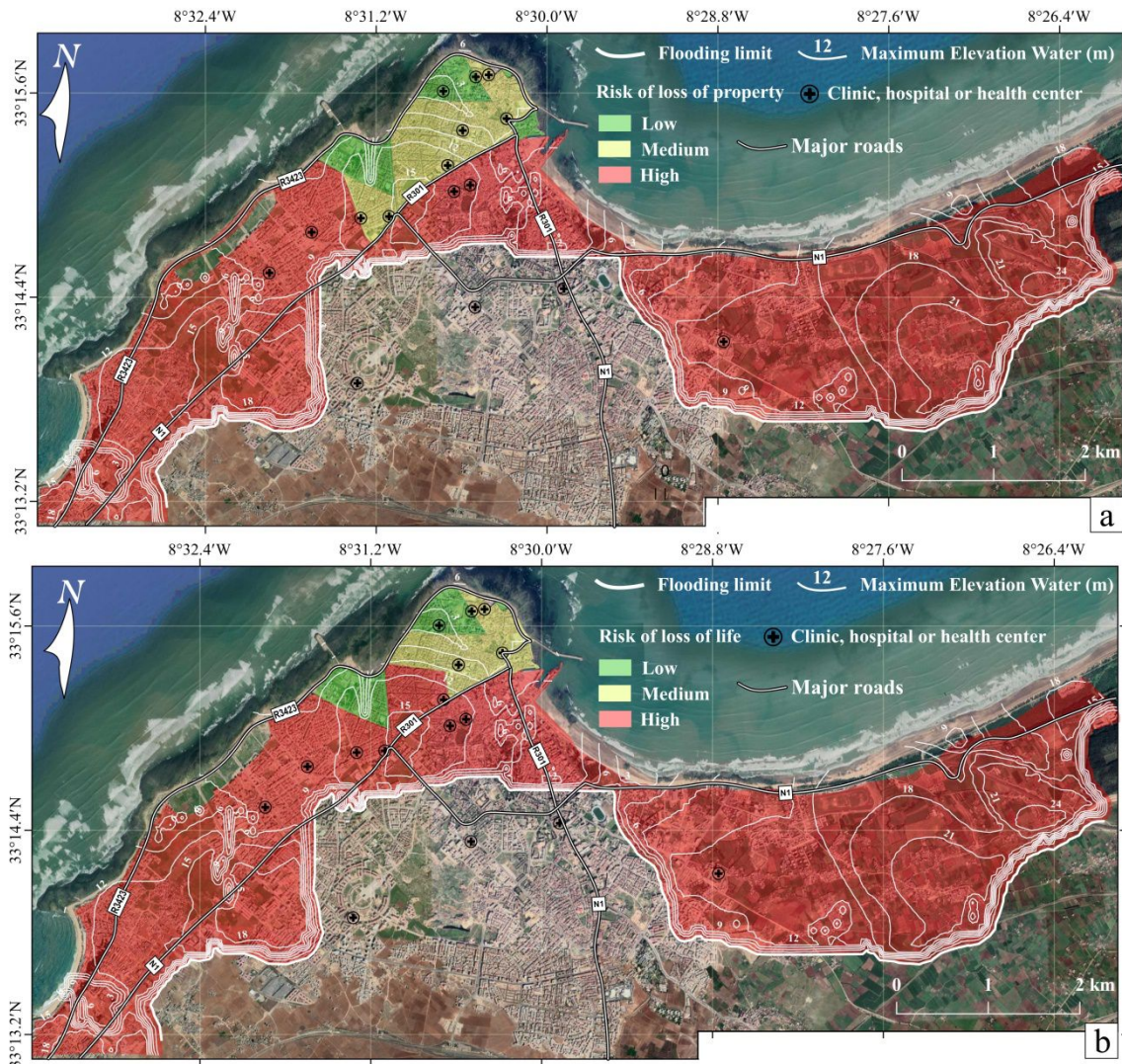
330 Figure 7: Maximum water elevation caused by the most credible earthquake scenarios in the Gulf of Cadiz  
 331 region. A: Result of Horseshoe Fault scenario; B: Result of Marquês do Pombal Fault scenario; C: Result of  
 332 Gorrige Bank Fault scenario. tf: final time for tsunami simulation; S: Scenario.

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

## 337 **4.2. Building damage and human loss estimations for El-Jadida**

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

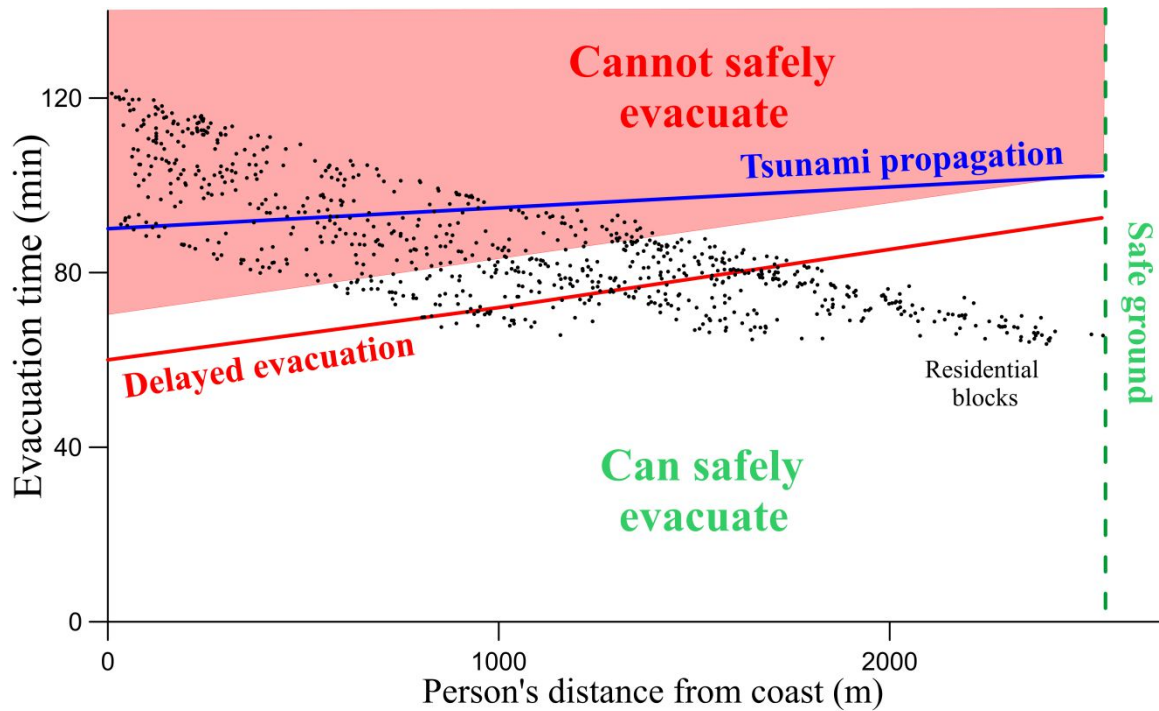
346 Although the assessment of economic risk is of importance, the  $R_{LOL}$  is the most crucial value to evaluate,  
347 especially in the case of rapid onset, large-scale natural hazards such as tsunamis, which could claim hundreds of  
348 thousands of lives in a matter of minutes. In the study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



358

359 Figure 8: Quantitative Risk estimation maps for El-Jadida city (source of background image: Google map

360 (<https://maps.google.com>) integrated in QGIS software as Basemap). **a.**  $R_p$  map. **b.**  $R_{LOL}$  map.



361

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

365 Table 3: Quantitative risk estimation result for El-Jadida city. Red : high risk. Yellow: medium risk. Green: low  
 366 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

<i>Road network/Streets</i>	52.54	0.03	-	-
<b>El Jadida</b>	<b>18744.07</b>	<b>14.48</b>	<b>108926</b>	<b>34.17</b>

367

## 368 5. Discussion

### 369 5.1. Limitations of the tsunami simulation

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

381 It is also important to note that parameters of active faults used to define the source areas for our simulations, are  
382 based on investigations conducted on the 1755 event and recent earthquakes, in the Gulf of Cadiz (e.g., Johnston  
383 1996; Hayward et al. 1999; Zitellini et al. 2001; Silva et al. 2017). The reason we only used the Horseshoe,  
384 Goringe Bank and Marquês do Pombal faults for our simulations is their high spatio-temporal seismic hazard,  
385 which has been demonstrated in many previous studies (Gutscher et al. 2006; Silva et al. 2017).

386 In addition, the inability of the simulation software to model wave propagation once tsunami travel time exceeds  
387 6120s has proven to be a great challenge when the Goringe Bank Fault was defined as the source for the  
388 tsunami generating earthquake (Fig.6-C). In our opinion, this is a significant limitation of this software  
389 especially when tsunamigenic earthquakes occur far from the coast. Nevertheless, MIRONE could still be  
390 considered a good tool for simulating near shore to medium range tsunami generating earthquake events, since  
391 results of simulations 1 and 2 (Fig.6-A and B) have proven to be similar to those obtained using commercial  
392 softwares (e.g. Omira et al., 2012).

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

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

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

## 413 **5.2. Reliability of the QRA method used in this study**

414 Although the QRA method proposed by Fell et al. (2005) takes into consideration all aspects of a given risk, it is  
415 seldom used in tsunami studies (e.g. Li et al. 2021). Our results show that this system can yield interesting  
416 results, allowing the assessment of economic and societal damages caused by tsunami events as well.  
417 Nevertheless, one must note that because the exact location of the 1755 source area and its precise recurrence  
418 interval remain uncertain, the calculated  $R_p$  and  $R_{LOL}$  values for El-Jadida city suffer from inaccuracies that  
419 cannot be numerically quantified. Indeed, the recurrence period suggested by previous studies range from 300 to  
420 2000 years (Ribeiro et al. 1996; Gutscher 2004; Ruiz et al. 2013), which means that the error if one extreme  
421 value or the other were used could be important. For this reason, an intermediate value of 1000 years was  
422 adopted in order to minimize the error and consequently avoid largely underestimating or overestimating the true



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

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

431 Moreover, one must stress the fact that this method only quantifies the value of property directly lost in  
432 consequence to the catastrophic event. Nevertheless, rebuild efforts and debris clean-up operations cost, as well  
433 as consequential damage to the regional economy of the area are not included in the QRA results. This is due to  
434 a lack of recent tsunami occurrences alongside the Moroccan Atlantic shoreline which could serve as reference  
435 points for the estimation. Despite the abundance of research elsewhere in the world, especially for the Japan  
436 2011 tsunami (Ghaderi and Henderson 2013; Naito *et al.* 2014; Maximenko *et al.* 2018), the particularities of the  
437 Moroccan economy makes it difficult to compare the results for both areas. In consequence, we consider that a  
438 post-disaster rebuild and clean-up will cost as much as building a new city from scratch. To do so, the unit price  
439 for urban infrastructure construction given in hectares is estimated to be around 1,3M\$ (MAUH 2012) which  
440 accounts for a total of 16.9 M\$ for the affected area. For house reconstruction efforts, a unit price of 1000\$/m<sup>2</sup>  
441 (Triantafyllou *et al.* 2018) is adopted to estimate the cost of rebuilding houses at the affected districts of El-  
442 Jadida, which totals about 1.3 B\$.

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

452 socio-economic problems related to acquiring land property for the construction of such structures. In this  
453 regard, we believe that the best solution is to install an operational early warning system and to educate the  
454 population about the danger of tsunamis and the locations of safe zones if such events were to occur. Although  
455 the most intuitive idea to protect the population against tsunamis is to build coastal defense structures, one  
456 should consider the important height of tsunami waves at the area ( $> 20\text{m}$ ) which is a true technical and  
457 economic challenge for the state. A better alternative will be the design of vertical evacuation structures in high  
458 risk areas in a way that allows the rapid evacuation of most people living in these districts. Ideas for the planning  
459 and design of such structures are proposed by Heintz and Robertson (2008); Park et al.(2012) and Wood et al.  
460 (2014).

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

## 465 **6. Conclusion**

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

473 For El-Jadida city, QRA results show that such events could be disastrous especially in the districts of Saada,  
474 Sidi Bouzid, Amal, Kaala and El Jawhara / Sidi Moussa, which are thus very high-risk areas. On the other hand,  
475 and despite its closeness to the shoreline, the Mazagan district, built on a low-elevation rocky cape might be less  
476 affected. Based on these results, we recommend establishing a tsunami response and mitigation strategy that,  
477 should allow for a quicker and more accurate intervention in the case of a future extreme event. The basis of  
478 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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