Tsunami risk and vulnerability analysis for the city of Rhodes

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ABSTRACT

The authors present a vulnerability and risk analysis of tsunami hazard for the city of Rhodes. The tsunami hazard is assessed through computed values of the maximum inundation and maximum flow depth derived from a probabilistic scenario for a 1000-year time window, which incorporates hundreds of numerical simulations with MOST code. The data needed to identify tsunami vulnerable areas are gathered combining remote sensing techniques and GIS technology with surveyed observations and estimates of population data. Tsunami risk zones are defined on the basis of both estimated maximum inundation and maximum flow depth data and results are presented using GIS.

KEY WORDS: tsunami; hazard; vulnerability; risk; Rhodes; Aegean Sea.

INTRODUCTION

Major tsunamis are rare events in the Mediterranean, where they are believed to occur a few times per century. Nevertheless, as historical records indicate, the island of Rhodes in SE Aegean has experienced severe earthquakes, such as the earthquakes of 1303, 1481 and 1741 AD, which are related, with variable degree of confidence, to the occurrence of tsunamis, see e.g. Ambraseys (1962), Papadopoulos and Chalkis (1984), Ambraseys and Synolakis (2010). Nowadays, the potential impact due to an extreme event is likely to be much greater since urban development is rapidly increasing in coastal areas.

Until 2004, there were limited studies on tsunami hazard and risk assessment, for specific locales in the Mediterranean Sea and particularly for Greece. Indicatively, Papadopoulos and Dermentzopoulos (1998) performed a qualitative tsunami risk pilot management study for Heraklion, Crete, their results being based upon the analysis of a hypothetical tsunami of a particular magnitude with no numerical modelling. Papathoma et al. (2003) and Papathoma and Dominey-Howes (2003) proposed a vulnerability approach incorporating various vulnerability factors in order to assign the so-called Relative Vulnerability Index to every building located inside the inundation zone. The latter was not derived from simulations but was rather defined as the area between the coastline and the 5m elevation contour. Their methodology was applied on a coastal segment of the western part of Heraklion and in the Gulf of Corinth. Birckmann et al (2010) analyzed the vulnerability of Cadiz, Spain and related it to what they refer to as "social dimension". Realizing that vulnerability variables are usually beyond the control of local communities, Ewing and Synolakis (2010) introduced a newer concept, the Community Resilience Index (CRI). This is tool for communities to evaluate resilience, whose factor can be modified by human intervention and thus it changes over time. They compare the response of Galveston, Texas, Tutuila, Samoa and Pacifica, California to Hurricane Ike, the 2009 Samoan tsunami and the California 2009/2010 winter storms, respectively.

In this study the authors present a vulnerability and risk analysis where the tsunami hazard is assessed by means of the outcome of multiple numerical simulations of tsunami events of a previous work, see Mitsoudis et al (2012). Specifically, vulnerable areas for the City of Rhodes are identified using results derived from probabilistic scenario for a 1000-year time window of Mitsoudis et al (2012).

Independently of the approach that one may follow in order to assess the tsunami hazard, there are specific data that have to be analyzed to subsequently identify vulnerable elements. To this end, the authors have determined the land cover/use for coastal areas from satellite images, identified and classified the main buildings and structures near the coast, and collected data for the population of the city and its seasonal variation. All the relevant data were integrated into a GIS platform and coupled with estimates of the maximum inundated area and the maximum flow depth, which were derived from the numerical simulations, to produce risk maps. These maps are presented with a GIS. This work aims into helping the city authorities to decide on suitable prevention and mitigation measures and strategies against a potential tsunami impact.

RHODES AND TSUNAMI HAZARD ASSESSMENT

Rhodes (Ρόδος) is the most populated island in the southeast Aegean region, located between the latitudes 35.85^o N and 36.5^o N and the longitudes 27.6° E and 28.3° E, opposite to the southeast coast of Asia Minor. Its homonymous capital city, surrounding the Medieval Town (which was designated as a World Heritage City by UNESCO in 1988), is located at its northern tip. The principal road network of the island radiates from the city along the east and west coasts. Both city and island population tend to grow contrary to the national trends for Greece; the total permanent island population is about 117,000, while the city of Rhodes has an official population of 54,000, according to the 2001 census; its actual population is estimated between 75,000 and 80,000. (This discrepancy may be mainly attributed to the fact that many permanent residents of the city register in the census at their place of birth which may be different.) Today, the island's primary source of income is tourism. It is estimated that the island is visited by about 2.8 million visitors (data regarding year 2008).

As already mentioned in the Introduction, Rhodes has been hit in the past by severe earthquakes which, some of them, are related in various catalogs to the occurrence of tsunamis, see e.g. Ambraseys (1962), Papadopoulos and Chalkis (1984), Ambraseys and Synolakis (2010). On the other hand, the entries in these catalogs number only a few events in the timescale of centuries. As noted by Ambraseys and Synolakis (2010), in the absence of geologic field studies and sedimentologic evidence, their occurrence should be considered tentative. Thus, since data on wave heights that would allow one to empirically assess the hazard are either limited or lacking, an alternative standard approach is through numerical simulations, with codes implementing efficient modeling of the various stages of tsunamis, i.e. generation, propagation and coastal inundation.

In this study, the earthquake-generated tsunami hazard for Rhodes is assessed by using results which are presented in Mitsoudis et al (2012). Therein MOST (Method of Splitting Tsunamis) code, cf. Titov & Synolakis (1998), coupled with accurate and updated bathymetry and topography data, was used for a large number of numerical tsunami simulations for Rhodes. Specifically, Mitsoudis et al (2012) presented results of four hypothetical, credible, near-field 'worst' case scenarios, associated with seismic events of magnitude 8.0 to 8.4, and also results based on multiple tsunami scenarios, incorporating uncertainties stemming mainly from the location of the seismic source, for time windows of 100, 500 and 1000 years. These inland inundation results were illustrated in terms of lines superimposed on satellite images, in the form of maps indicating the estimated maximum values, or in terms of two-dimensional histograms reflecting the extent as well as the frequency of the corresponding hazard parameter.

The results indicated that the impact of the most hazardous deterministic scenarios was overall smaller than the 1000 years probabilistic results which incorporated hundreds of scenarios (see Figs. 1 and 2). Here, the authors have decided to use as a basis for the vulnerability and risk analysis which follows, the estimated values of the inundated area and the maximum flow depth that were derived by the probabilistic scenario for a 1000 year time window.
The choice relies on the fact that the specific scenario combines results of multiple tsunami simulations, incorporates uncertainties associated, mainly, with the location of the seismic source, and seems to have a stronger impact on the city of Rhodes. An alternative approach would have been based on assigning some probability to specific areas and relating it with the associated risk by using other results presented in Mitsoudis et al. (2012), particularly two-dimensional histograms for different time windows showing the frequency with which a specific area is inundated and the number of times that the maximum flow depth exceeds a specific threshold. It was decided not to do so in order to avoid possible underestimation of the potential impact and risk, and keep our analysis as simple and comprehensive as possible.

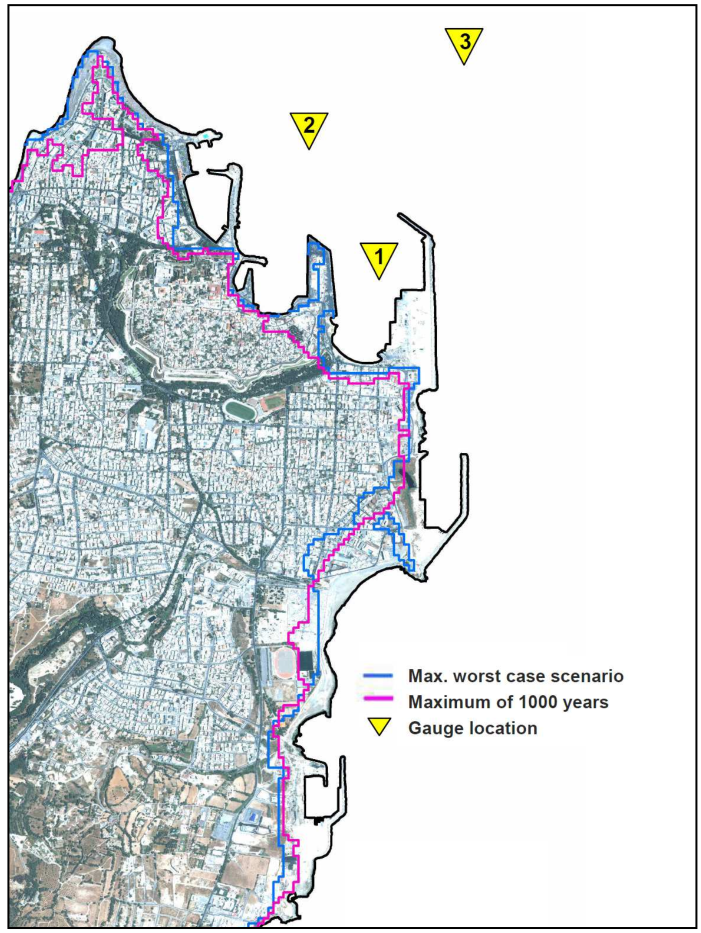

Figure 1. Comparison of a probabilistic maximum inundation line for a time window of 1000 years versus the maximum inundation line for a deterministic scenario, superimposed on a satellite image of the city of Rhodes (after Mitsoudis et. al 2012).

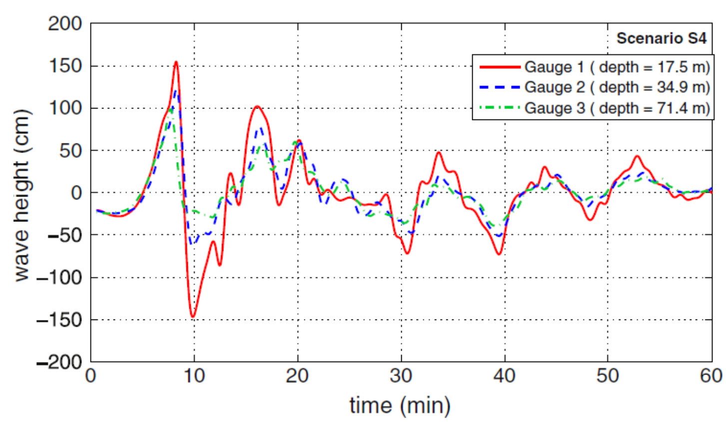

Fig. 2. Computed time series of wave elevation at three virtual wave gauges for the deterministic Scenario S4 of Fig. 1 (after Mitsoudis et. al 2012). Gauges' location is marked with yellow triangles in Fig. 1.

VULNERABILITY ANALYSIS

The concept of vulnerability is understood in many different ways and, in general, it refers to the exposure or the degree of resistance to a hazard. Among tens of definitions, see Birkmann (2006), one may broadly define tsunami vulnerability as the set of objects, conditions, variables, and processes resulting from physical, social, economic, and

environmental factors, which increase the susceptibility of a community to a hazard. In order to assess tsunami vulnerability, with respect to a specific tsunami event, various data sources and techniques are used to identify the exposure of critical elements to tsunami hazard. Typical “elements” include population, buildings, roads, ports, infrastructures as well as various social or economic aspects. Tsunami vulnerability in populated coastal zones may be characterized by strong spatial variations according to the location of elements, and may be also subject to temporal changes in case of e.g. variation of population in a seasonal scale or even in a 24-hour scale.
In what follows the authors present a vulnerability analysis for the city of Rhodes which may be summarized into the following three main steps: (a) collection of data from various sources for critical elements lying in the coastal zone, (b) integration of datasets in a GIS platform, and development of databases and GIS layers, and (c) identification of vulnerable elements based on the probabilistic scenario for a 1000 year time window of Mitsoudis et al. (2012), and production of maps.

Data collection, databases and GIS layers

Data concerning land cover/use for coastal areas, buildings and important structures near the coast, road network, as well as data and estimates for the population and its seasonal variation, were collected and classified. For the detection of geographic locations, Remote Sensing data and techniques, Geographic Information System (GIS) technology, and field surveys were used. It should be noted that the adoption of GIS technology provided the appropriate tool not only for mapping, but also for organizing and analyzing data in separate layers. In what follows, this process is described in detail.

Urban areas detection& Land Use / Land Cover mapping

In order to detect urban areas, the coastal zone was traced and Land Cover/Land Use (LC/LU) data were derived from satellite images. To this end two different remote sensing techniques were used to produce a general mapping of urban areas with elevation lower than 50m, and a detailed LC/LU mapping with elevation lower than 20m.

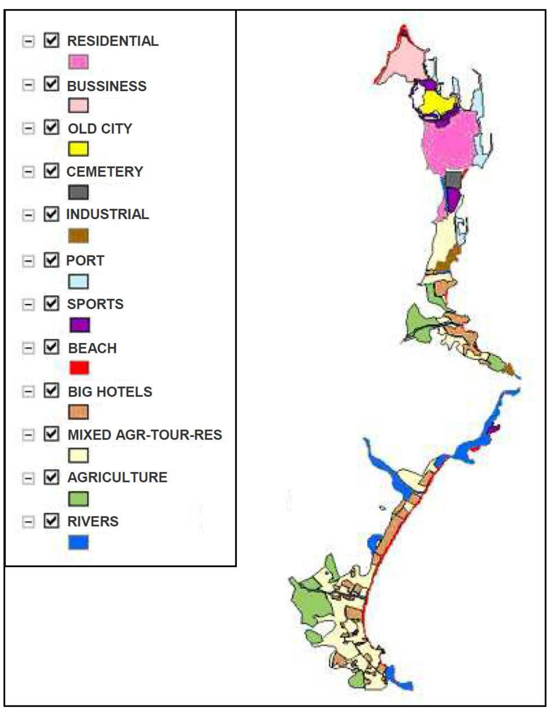

Figure 3. LU/LC mapping in the main urban zone of the study area.

Initially, the urban area detection was performed with the use of High Spatial Resolution (HR) ASTER multispectral satellite imagery covering the NE half of the island of Rhodes, with spatial resolution of 15m, and positional accuracy of 15m. The image was orthorectified and classified into 11 classes by employing a per-pixel supervised classification procedure. Then, a post-classification sorting merged the classes into two main categories: (i) urban/beaches, and (ii) non-urban. (Urban areas are defined as areas with man-made structures). Areas that contain man-made structures with elevation lower than 50m, as well as the beaches were extracted, Chrysoulakis, et al (2008).

Next, a more detailed survey was performed using Very High Spatial Resolution (VHR) satellite imagery. IKONOS multispectral satellite data with spatial resolution of 1m and positional accuracy better than 2m were used. Combining multispectral imagery with high resolution panchromatic results, 1-meter color images were produced. An accurate DEM (RMSEz better than 1m) was used both for the orthorectification of the resulting images, and for extracting all pixels corresponding to areas with elevation less than 20m. The extracted area was then divided to 12 classes of LU/LC, shown in Fig. 3, with a semi-automatic classification method (Chrysoulakis, et al 2008). The extracted classes were: Residential, Business, Old city, Big Hotels, Beach, Sports, Agriculture, Industrial, Mixed agricultural & touristic residence, Port, Rivers, and the Cemetery.

Table 1. Building classification according to height and type of construction.

Building Categories (Height, Type)

Height		Type	
a	up to 1 floor	a	Old (stone)
b	up to 2 floors	b	1960’s type
c	up to 4 floors	c	1980’s type
d	> to 4 floors	d	Modern

Figure 4. Example photographs of main buildings of Rhodes with their classification (height, type) codes.

Buildings

The IKONOS data was also used to detect 150 major buildings located in the NE coast of the island. Information on building height and type was also extracted (with the aid of GoogleEarth/Panoramio: http://earth.google.com) and stored in a database. A classification scheme of four building height classes (in one-floor increments) and of four building types (old - masonry made, 1960’s type, 1980’s type, and modern) was developed. Combining these two schemes, 16 categories of (height, type) pairs were defined, as shown in Table 1. In Fig. 4 photographs of representative examples of buildings are shown together with their classification parameters.

The extracted data on building location, orientation, type and height were validated and corrected using in-situ observations during a field campaign in July 2008. In Fig. 5, the polygons of the buildings in the north edge of the city are superimposed on the IKONOS satellite image. The color of each polygon is associated with the classification codes of the buildings, as defined in Table 1. Data for these buildings (name/use, location, height, type and orientation) were uploaded in a GIS system, and will be henceforth referred to as the Building Database.
Since the coastal area of Rhodes hosts many hotels, a subset of the building database refers to them. Each hotel has been included, identified and extra fields such as the number of beds have been added.

Figure 5. Map of the classified buildings in the North part of the city of Rhodes.

Estimates of Population and its seasonal variation

Human life is the most important element at risk during tsunami attacks, thus population data for Rhodes were collected from all available sources, and the population in the coastal zone was estimated, since generally available such data are usually incomplete.
At first, the authors integrated in the GIS platform the distribution of permanent population exploiting data, in the form of number of residents for each city block (2001 housing census), obtained for the municipality of Rhodes from the National Statistical Service of Greece.
Other than spatial variations, the population of Rhodes has a significant seasonal variation due to the high tourist activity and visitors influxes. The tourist period usually starts around May 1st and lasts until October 31st, with the high season in July and August. The main port and the only airport of the island are within the city limits of Rhodes.
In order to estimate the seasonal variation of the population the authors used: (a) departure and arrival data for the Rhodes airport from the Greek Civil Aviation Authority for the period 2000-2008, and (b) data on the total arrivals at the airport and port of the city of Rhodes in 2007 and 2008, thus it was estimated that the island is visited by about 2,800,000 tourists mostly during the summer. Assuming a mean length of stay is 10 days, and a uniform distribution of tourists during the period May-October (which is an underestimate for the high season of July and August), results in ~156,000 visitors (28 millions x days / 180 days) per day. A percentage of 80% of the visitors stay in the city of Rhodes, since it combines museums, historical sites, sandy beaches, sea sports, nightlife, and has a high number of hotels and rooms for rent. Thus, a conservative estimate is that approximately 120,000 tourists stay in the city of Rhodes each day during the tourist period, leading to the conclusion that the population of the city reaches up to ~200,000 people, an increase of about 2.5 times over its permanent population.

Road networks, ports and piers

The principal road network of the island radiates from the city along the east and west coasts. The road network of the city of Rhodes is gradually becoming insufficient as cars expand at a rate of 5,500 vehicles per year, making both traffic and parking an increasing concern for the city, especially during the high-season (about 70,000 vehicles move from/to the center of Rhodes per day). Practically most of the traffic occurs outside the walls and close to the port, while there are cases where main roads are adjacent to the coast and in low elevation areas. In some stretches (e.g. close to Akti Sachtouri), the main road is lying just between the beach and the fortification of the Medieval Town. Such roads are potentially exposed to tsunamis, and it is important to identify them in a vulnerability study, both from the point of view of potential number of casualties (e.g. vehicles on the road), but also because people will try to use them to evacuate, a practice that would be catastrophic.
Ports and harbors are also exposed. The port of Rhodes was famous in ancient times for the Colossus of Rhodes, one of the Seven Wonders of the World. Today the city has four harbors, each of these ports has one main long pier, at times full of passengers, vehicles, cargo and port workers.

Identification of vulnerable areas and elements

After collecting, verifying and organizing all previous data, and its integration in the GIS system, the vulnerable elements were identified using the tsunami-hazard assessment of Mitsoudis et al (2012). To this end, their maximum inundation line data computed as the maximum penetration over 100 numerical simulations for near field tsunami events in a 1000-years time window for Rhodes, were used. Inundation lines were also uploaded in the GIS system, thus defining the vulnerable areas and elements located between this line and the shoreline.
The number of population in inundated buildings is estimated by superimposing in the GIS the inundation line on the population per city block data, and is found to be 2,366 permanent residents. Taking into account that this represents about 70% of the actual population, a total of 3,400 permanent residents is assumed, plus an estimated 10,000 people working in businesses and services in the inundated zone are at risk.

Table 2. Estimates of population in inundated areas.

Population type	Time period	Approximate totals
Permanent residents	All time	3,400
Business / services	Working days and / or tourist season	10,000
Hotels	Tourist season	10,000
Beaches	Mid-day hours, high season	100,000

The above refers only to the permanent residence. The number of hotel guests in the inundated area was extracted to be around 10,000 according to the Hotel database. Moreover, most of the visitors during the summer spend a lot of time on the beach. For this reason, the area of the beaches (as defined in the LU/LC mapping) has been calculated to be 111327m^2. This area includes five beaches close to the city, namely Elli beach, Akti Kanari, Akti Miaouli, Akti Sachtouri, and

Zefiros beach. During a field-trip of July 2008, the authors estimated that the population density in a typical beach may reach 1 person per m^2 during mid-day hours. Thus, it is possible that ~100,000 people may be at these beaches during these hours. Table 2 summarizes our estimates of population at risk.

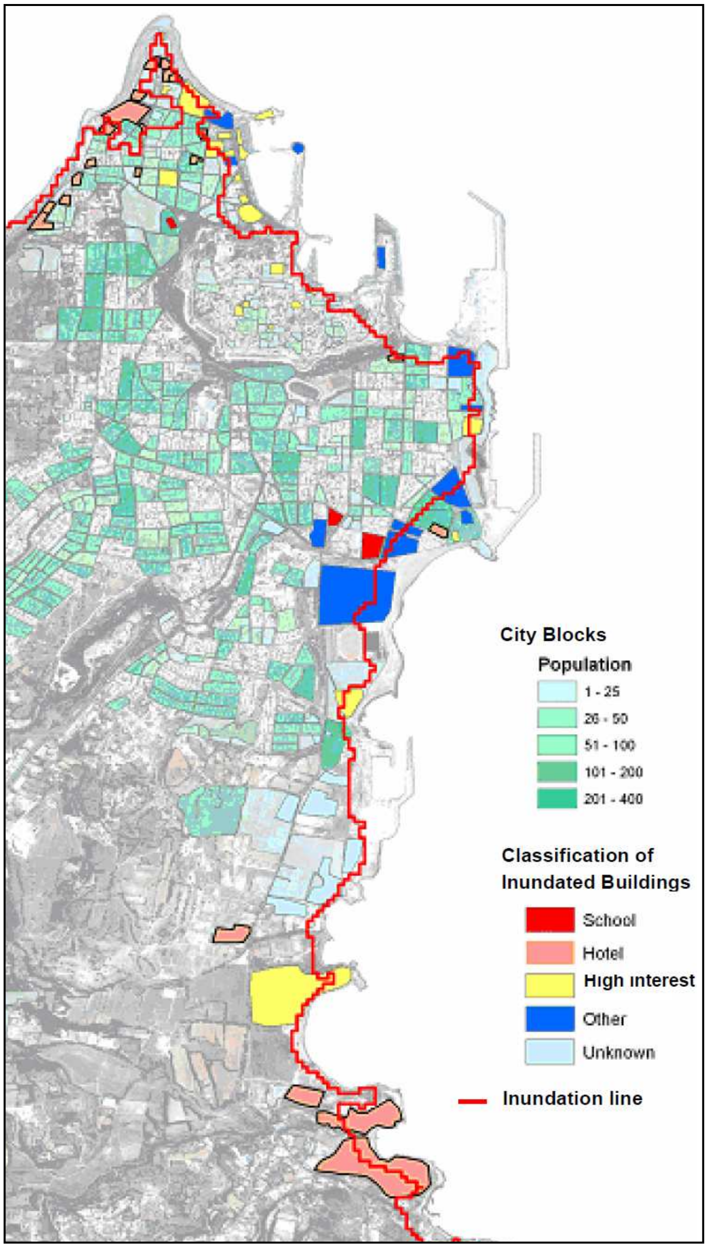

Figure 6. Classification of inundated buildings of interest.

In Fig. 6, some important buildings or city blocks in the potentially inundated zone are shown. Specifically, buildings that: (a) may house a large number of people, e.g. schools, churches, theaters, etc., during some specific time periods, and (b) may host public services and authorities who will have a major role in case of a tsunami or other natural disaster. Five categories of buildings are distinguished including schools, hotels and sites of high interest, depicted on a map showing the classification of city blocks according to population.
In Fig. 7, a classification, based on their height, of the main buildings that may be flooded (cf. Table 1 for classification codes) is presented. Buildings in red are single-floor structures, therefore more vulnerable.

RISK ANALYSIS

Having identified vulnerable elements including buildings, population, roads, etc. in the inundated area, the next step is to estimate the risk that these elements are subject to. According to a standard definition, risk may be viewed as the vulnerability multiplied by the hazard. Of course, the identification of the nature and extent of risk is subjective and influenced by perceptions and willingness to adapt.
Here, a simple and practical approach to risk assessment is adopted. The tsunami hazard has been assessed on the basis of a probabilistic scenario (cf. Mitsoudis et al (2012)), and vulnerability is considered in terms of the maximum inundation suggested by this scenario. Then, various parameters and metrics indicating the tsunami intensity, and thus the potential of loss or damage could be taken into account, Wegscheider et al (2011), and the estimation of risk could be based on the values of damage metrics of the tsunami hazard (e.g. flow depth, current speed, momentum flux, etc). Here, as a first-order approximation, the risk of the vulnerable elements is estimated according to the maximum flow depth (FD), computed in the simulations, and three zones of risk are distinguished inland following Table 3 .

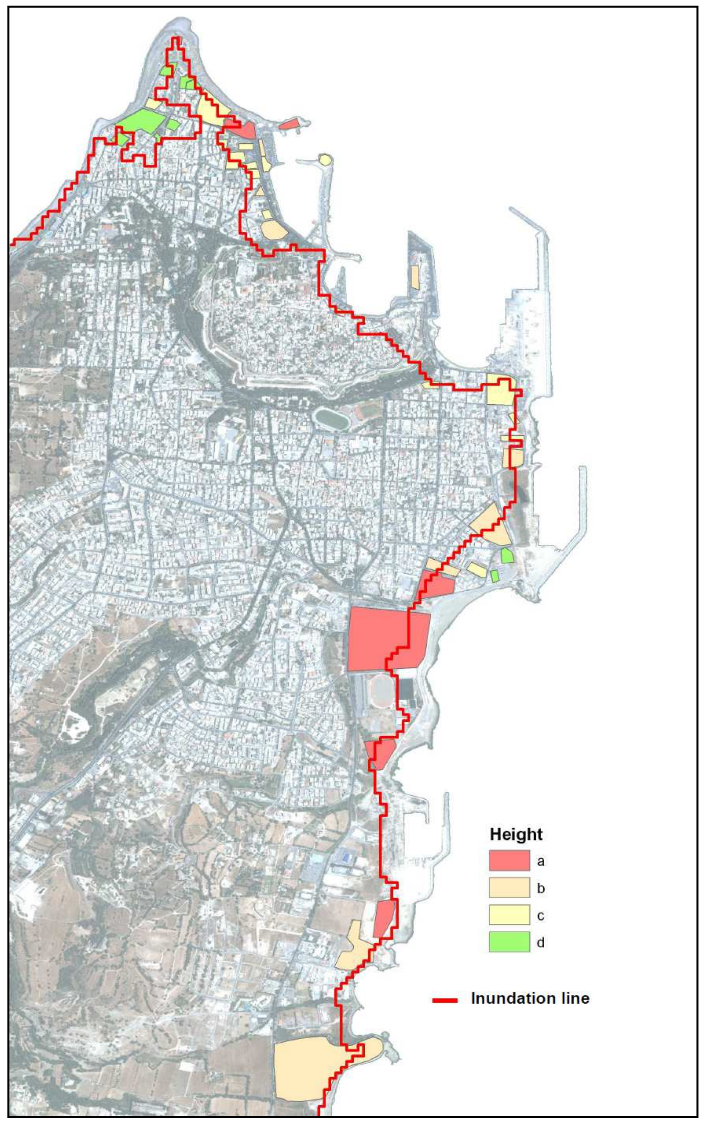

Figure 7. The main buildings at risk classified according to their height.

Next, the authors present 'risk maps' derived using GIS technology to connect the flow depth and vulnerability map layers. Figure 8 shows the area of study, the 1000-year inundation line, and the risk zones B and C in different colors. One can notice that most of the inundated area is in the high risk zone including all beaches, ports, piers.

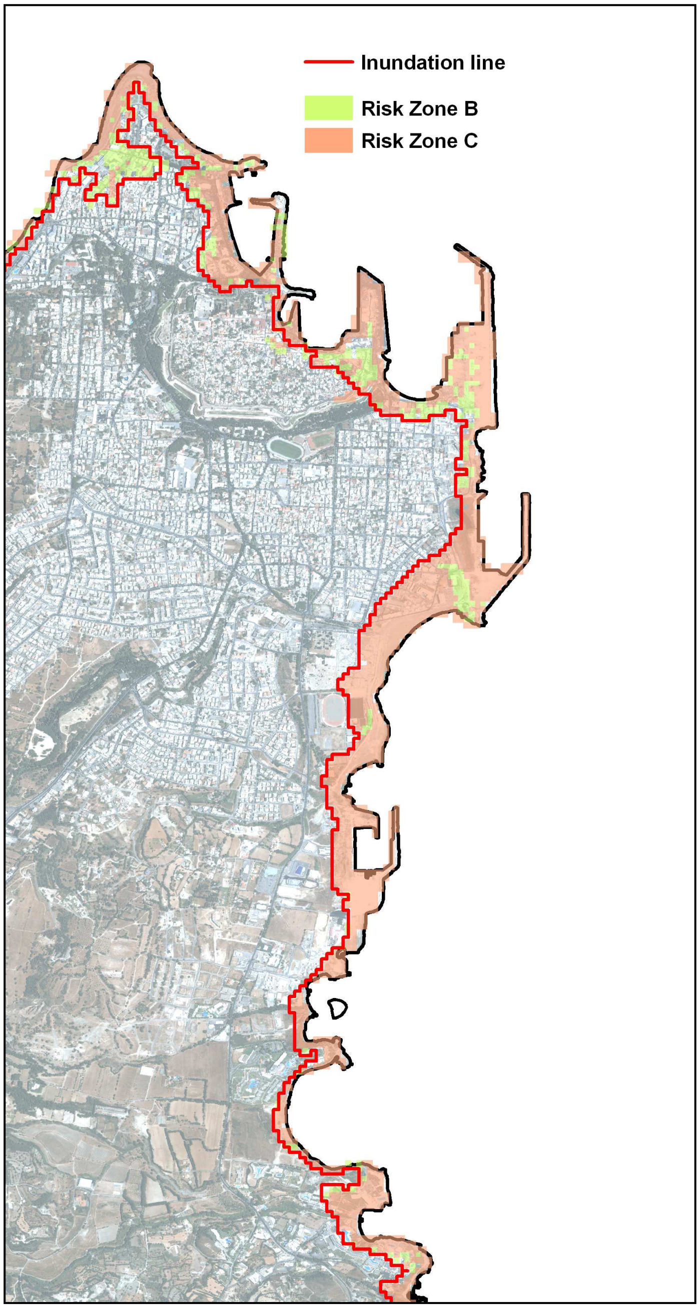

Figure 8. The study area with the inundation line and risk zones B and C for the 1000-year probabilistic scenario.

Table 3. Tsunami risk zones for the city of Rhodes.

Risk Zone	Definition	Risk
Zone A	FD = 0 (Dry land)	no risk
Zone B	0 < FD < 1 m	medium
Zone C	FD > 1 m	high

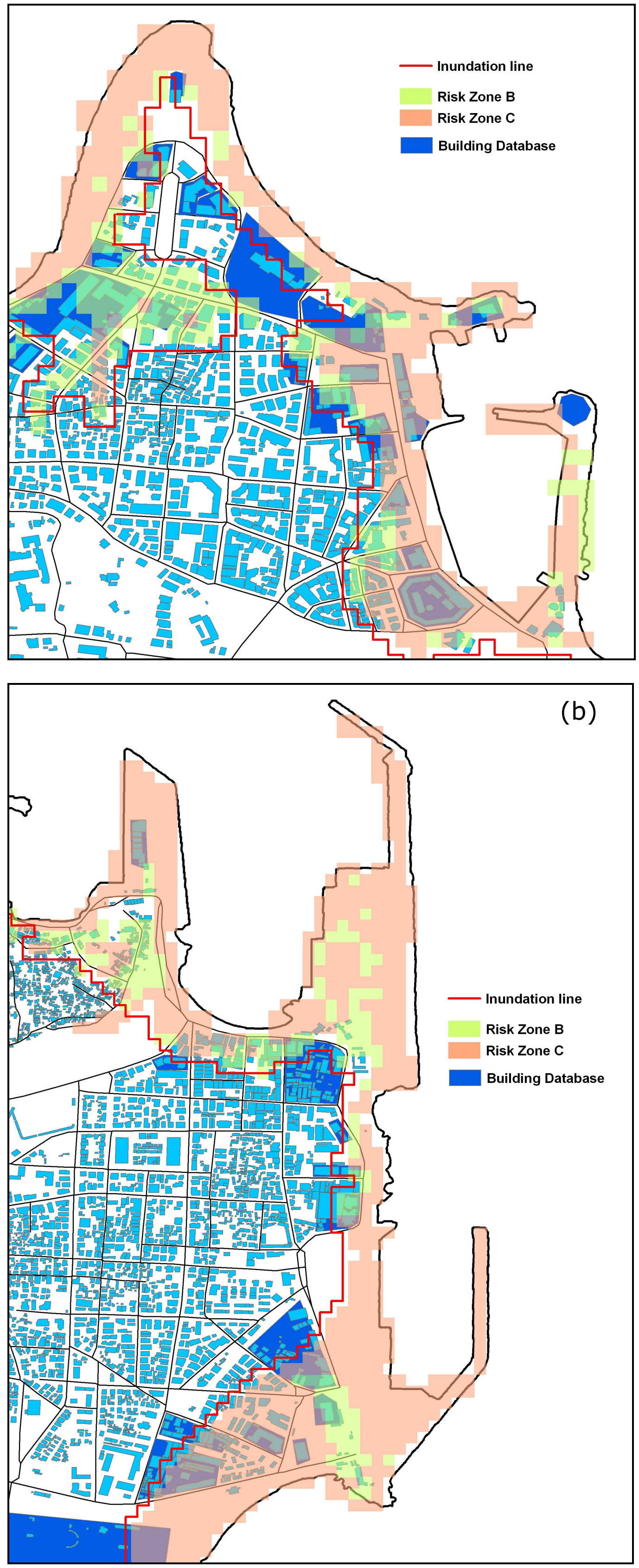

Figure 9. Risk map showing the risk for buildings and other man-made structures for (a) the northern part and, (b) the eastern part of the city.

In Fig. 9, the risk zones are superimposed on a map of buildings, roads and other man-made structures for the northern (9a) and eastern (9b) parts. In addition to beaches and harbors, several buildings and sites lay within the risk zones B and C as well as an extensive part of the main road network. The later is depicted more clearly in the risk map of the central part shown in Fig. 10, which includes also the main ports and the medieval town. As it can be seen, several main roads are at risk, and some of them lie in Zone C, which indicates a flow depth exceeding 1m.

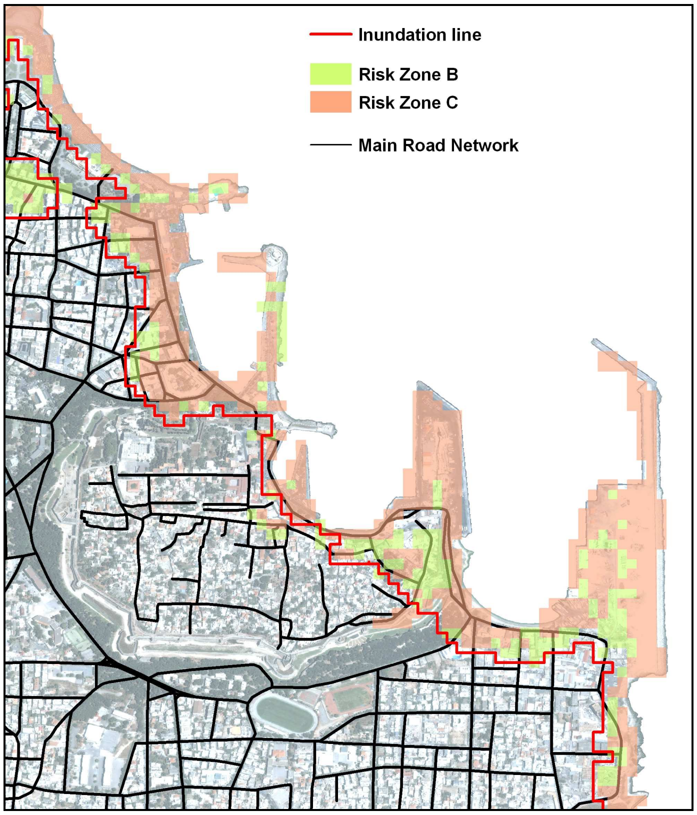

Figure 10. Risk map of the central part of the city of Rhodes (including the ports and the medieval town), showing the risk for the road network.

DISCUSSION AND CONCLUDING REMARKS

Here, a tsunami vulnerability and risk study for the city of Rhodes was presented. The results were depicted in maps that could assist emergency planners and local authorities in their consideration in planning for natural disasters mitigation. It should be stressed that the tsunami arrival times calculated in Mitsoudis et al (2012) are very short (<20 min). This suggests that, there will be probably only a several minutes time interval between the occurrence of a tsunami-generating earthquake and the tsunami's arrival on the coast, hence the following basic recommendations should be considered by the emergency managers of the city.

1. General recommendation to the public: In case of a significant earthquake, people in beaches, ports, piers, and coastal areas that are vulnerable to inundation should immediately move to places with higher elevation. This general advice should be repeatedly stressed to the public through the educational system and the media. Also, special signs should be posted in the most vulnerable areas including of course the beaches.

2. Evacuation of buildings: The main practical question is whether the buildings that lie inside the flooded area should be evacuated or not.

We recommend the following:

Zone A: Buildings lying in zone A need no evacuation.

Zone B: Buildings in zone B should be evacuated if they have only one floor. For buildings in zone B with at least two floors, residents should move to the second floor (vertical evacuation).

Zone C: Buildings in zone C should be evacuated, if they have more than two floors. For buildings in zone C with at least three floors, residents should move to the third floor (vertical evacuation).

3. Roads, Ports and Piers: As it has been already mentioned, special attention should be given to coastal infrastructure. In the city of Rhodes, a 1000-year tsunami is estimated to flood all parts of the main commercial and tourist harbors. It is very important that all people working in the ports and piers should be educated on tsunami hazards, so that they self evacuate their area of work in case of an earthquake and/or unusual high amplitude water oscillations within the harbor. As the main road adjacent to the coast is expected to flood, local authorities should plan for alternative evacuation routes.

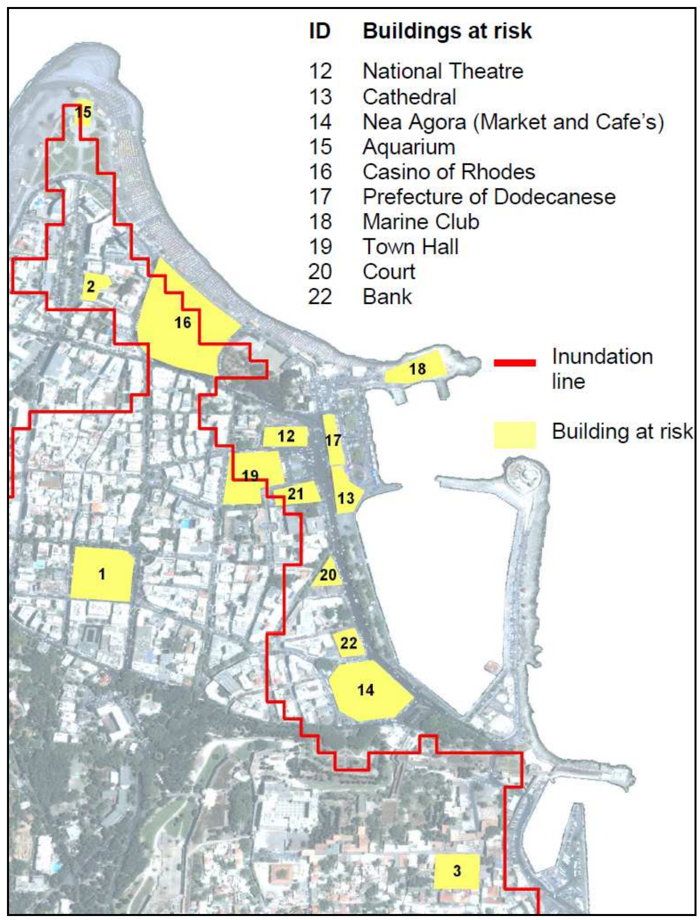

Figure 11. Buildings of special interest and 1000-year inundation line.

4. Public buildings and sites of special interest: Special attention should be given by the authorities to public buildings and sites of special interest (cf. Figs. 6-7). Specifically, buildings that may house a large number of people, e.g. schools, churches, theaters, etc., during some specific time periods, they may also host public services and authorities who will have a major role in case of a tsunami or other natural disaster. As an example, major buildings of this type are indicated in Fig. 11, for a specific coastal area (Mandraki). Local authorities should make complete lists of all other important structures and sites that may also be of special interest.

It should be noted that all these results are meant to help civil protection agencies draw emergency plans and improve resilience, and are only appropriate for comparing relative vulnerabilities. As the 2011 Japan tsunami demonstrated (Fritz et al, 2011), flooding from any particular event may exceed even 1000-year estimates. In the present work case, rather conservative scenario events for the Eastern Hellenic were used, but the fact remains that the Hellenic Arc is possibly the least understood of the world's subduction zones. Future earthquakes may be larger than the scenarios used here, hence tsunami assessments need to be continuously revised as new information on Aegean neotectonics becomes available (Floyd et al, 2010) and as land use and construction changes.

Ending, it should be noted also that the primary database, which was built in the GIS for this work, allows easily for the examination of alternative tsunami hazard scenarios, and for additional risk criteria based on other damage metrics.

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