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Assessment of Coastal Vulnerability for Present and Future Climate Conditions in Coastal Areas of the Aegean Sea

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ABSTRACT: Vulnerability to flooding for two coastal areas of the Aegean Sea (Chania at Northern Crete Island and Thrace at Northern Greece) is assessed taking into account climate change effects. Two approaches are applied for the present (1951-1999) and future conditions (2000-2049,2050-2099).
A Flood Vulnerability Index (FVI) is estimated based on run-up and storm surge computations for both present and future climate. Run-up is calculated from an empirical formula based on area morphology and wave climate, derived from a Digital Elevation Model of the areas of study and the SWAN wave model, respectively. For the complete description of the morphology of the areas, an adequate number of cross-shore profiles is created at each site. SWAN model is forced by wind data from RegCM3 according to emission scenario A1B SRES of IPCC. On the other hand, storm surge is calculated from the MeCSM hydrodynamic model forced by wind and pressure data from RegCM3 for the same emission scenario.
The first approach uses cluster analysis to classify all storms and then evaluates total water level ($Ru+\xi$) for each class in order to estimate the corresponding FVI. The second one evaluates Ru for the maximum annual storm, uses extreme value analysis for extracting the total water level which corresponds to return periods of 50, 100 and 500 years and then estimates FVI for each area.
The results highlight that the area of Chania is very prone to flooding. Both methodologies indicate very high vulnerability for the majority of the selected beach profiles describing the area. For the area of Thrace the first methodology indicates that 45% of the cross-shore profiles for present and 55% for future wave climate show very high vulnerability to flooding. The second one implies that for extreme waves and storm surge with a return period of 50 years or more, the area is prone to flooding for both the present and future conditions.

Keywords: Vulnerability, Flooding, Coastal, Climate change

1 INTRODUCTION

Coastal areas are of great importance for prosperity and economy of human societies. In EU these areas are inhabited by approximately 200 million people and they should really be protected, in a context of rapid globalization and climate change. In 2007, EU proposed and developed the Floods Directive 2007/60/EC (FD) in order to reduce and manage the risk of flooding affecting environment and human societies and activities. This stresses the importance of the assessment of coastal vulnerability to flooding.

Vulnerability, according to the recommendation of the FLOOD*site* project, is the potential of a system to be harmed by a hazard (Gouldby and Samuels, 2007). However, the complexity of the morphology and dynamics of the coastal areas makes it very difficult to adopt a common methodology, for the evaluation of vulnerability to flooding. The IPCC's Common Methodology was the first method to be widely applied to assess the vulnerability of countries to sea-level rise (IPCC, 1992). However, the methodology lacks the flexibility to consider factors of critical significance. In 1991, Gornitz et al. developed and proposed the Coastal Vulnerability Index (CVI) which was widely applied at USA and Canada coastlines. A more complex index, Coastal Social Vulnerability Index (CSoVI) was proposed by Cutter et al.(2003) which combines CVI and some socio-economic parameters. The CSoVI is a combination of variables for North America and Australia coastal regions. Another effort for the assessment of coastal vulnerability was proposed by McLaughing and Cooper (2010), but it was focused mostly at the vulnerability to erosion rather than that to flooding. For the coasts of the Aegean Sea, there are very few studies (Alexandrakis et al., 2009) concerning the assessment of vulnerability to sea level rise, indicating that approximately half of the Aegean (Hellenic) coastline is of medium vulnerability, with the other half being highly vulnerable.

In this paper, the coastal vulnerability to flooding is assessed by applying two separate methodologies, both evaluating a FVI based on run-up (Ru) and storm surge (ξ). The first one, proposed by Mendoza and Jimenez (2009), classifies storms according to their energy content (E) and then evaluates the average Ru and ξ for each class. It is developed for and applied to the beaches of Catalan coast, but it can be easily adopted for any coast in the Mediterranean Sea. The second methodology, proposed by Bosom and Jimenez (2011) is a probabilistic approach where extreme values for Ru and ξ, with a given return period, are used after fitting an extreme probability distribution with annual maximum storms . These two approaches are applied to two coastal areas of the Aegean Sea (Chania and Thrace) in Greece.

In the following, an analytical description of both approaches, information about wave climate and area data used, derived results and conclusions, are presented.

2 METHODOLOGIES

The first step before applying the two approaches is the characterization of the forcing (storm). A storm is defined as the event exceeding a minimum significant wave height (H_s) and with a minimum duration of 6 hours. This criterion was proposed by Mendoza and Jimenez (2008) as the minimum conditions required to generate a significant impact to each coast.

2.1 *1st approach: FVI based on storm classification*

The basic idea of this approach was to group storms into classes based on similar characteristics and evaluates coastal vulnerability for each class, instead of studying their consequences individually. An index (FVI) is used in order to estimate coastal vulnerability, which is correlated with wave data sets (Ru is evaluated for the maximum significant wave height H_s of each storm and corresponding values of wave peak period T_p), storm surge (average value for each storm class) and beach morphology data (beach slope and beach/berm height).

After the definition and identification of the storms, the energy content (Dolan and Davis, 1992) is used for their classification into 5 groups (I-weak, II-moderate, III-significant, IV-severe, V-extreme).

$$E = \int_{t_2}^{t_2} H_s dt \tag{1}$$

where (t_1-t_2) is the storm duration.

For the classification of the storms, hierarchical agglomerative cluster analysis is carried out. Ward's minimum variance method is used.

The next step consists of quantifying the hazard. The maximum elevation of the sea level, which is calculated as the sum of run-up (Ru) and storm surge (ξ) is defined as a hazard. The empirical formula proposed by Stockdon et al. (2006) is used to calculate the Ru for each storm.

$$\mathrm{Ru} = 1.1\left(0.35\tan\beta\left(H_s L_0\right)^{1/2} + \left(H_s L_0 \frac{\left(0.563\tan\beta^2 + 0.004\right)^{1/2}}{2}\right)\right) \tag{2}$$

where H_s is the maximum significant wave height of each storm, tanβ is the beach slope and L_0 is the deep-water wave length associated to the wave peak period (T_p) for each storm. For each value of the maximum H_s, a concurrent value of ξ is selected. The final Ru for each class is obtained by taking the average of the Ru calculated for all storms within the class.

For evaluating the FVI, an intermediate parameter is used (FIP), as given by Mendoza and Jimenez (2009),

$$\mathrm{FIP} = \frac{\left(\mathrm{Ru} + \sigma_{\mathrm{Ru}}\right) + \xi}{\mathrm{B}} \tag{3}$$

where σ_{Ru} is the standard deviation of the Ru calculated for all storms within each class, ξ is the average storm surge of each storm class and B is the berm height. In many cases the profiles of Greek beaches do not have a berm, hence B is considered as the beach height at the end of the beach.
Once FIP is known, FVI is obtained using the functional rule shown in Figure 1 (Mendoza and Jimenez, 2009). According to this function the "safest situation" (zero vulnerability) for a storm class, is when the representative total water level is less than the beach/berm height ($B > 2(Ru + \sigma_{Ru} + \xi)$). On the other hand, the highest vulnerability is assigned when the beach/berm height is lower than the total water level ($FIP > 1$). Between these two situations the FVI is linearly increasing with FIP and is divided into 5 categories: Very Low - Low - Medium - High - Very High.

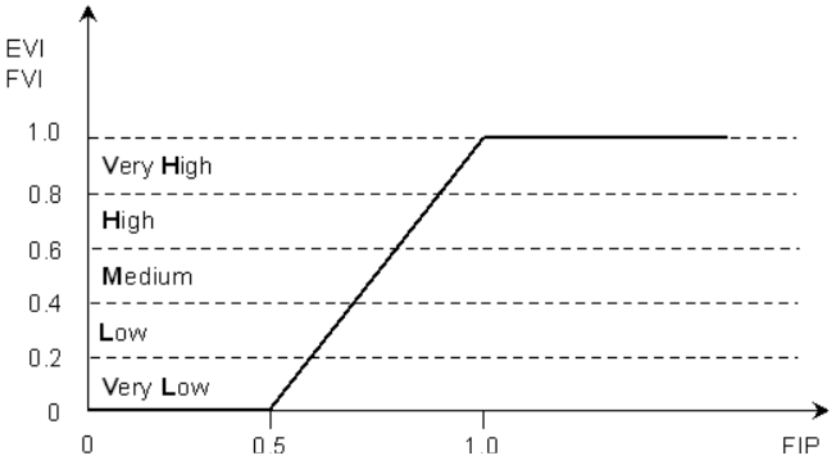

Figure 1. Evaluation of FVI

2.2 *2nd Approach: FVI based on Extreme Value Analysis*

With the second approach, FVI is also used for the evaluation of coastal vulnerability (Fig.1). The main difference with the first methodology is that the values of the variables (Ru, ξ) used for the estimation of FIP are assessed by means of extreme value analysis. Annual maximum H_s are utilized to estimate the corresponding Ru values and then an extreme probability distribution is fitted to the data. Extreme probability distribution is fitted to annual maximum values of ξ, too. A more detailed overview of the methodology is presented below.

The first step of this approach is the quantification of the total water level. For each year, only the maximum storm is taken into account. The maximum H_s of the maximum annual storm is used calculating the annual maximum Ru, according to Equation 2. Annual maximum values of ξ are, also, obtained.

Afterwards, the annual maxima of Ru and ξ are modelled using a univariate generalized extreme value (GEV) distribution function. The parameters of the GEV are estimated by the Maximum Likelihood Estimation procedure (MLE). In cases where the MLE procedure resulted in inadmissible results for the marine data e.g. strongly heavy tails, the procedure of L-moments is used to estimate the parameters of the model. The return levels extracted using the GEV distribution function corresponds to return periods of 50, 100 and 500 years.
The final step of this methodology is to evaluate the FVI. The expression proposed by Bosom and Jimenez (2011), which is used to calculate the FIP is

$$FIP = \frac{Ru + \xi}{\mathrm{B}} \tag{4}$$

where Ru and ξ are the values of run-up and storm surge correlated to the given return period, respectively. After FIP is calculated, the functional rule is used (Fig. 1) for the estimation of FVI. As mentioned above, two boundary conditions (for zero and highest vulnerability) and five categories of vulnerability were designated.

3 STUDY AREAS

The two study areas are located in the Aegean Sea (Fig.2). The first one is the coast of Thrace (NE Aegean Sea) and the second one is the coast of Chania at SW Aegean Sea (NW Crete Island). The information and variables about their geomorphologic characteristics are extracted from a Digital Elevation Model (DEM) with lattice dimension of 5m, by using free GIS software.

An adequate number of cross-shore profiles are taken perpendicular to the given beach contour for each area, for the complete description of the morphology and the production of a comprehensive picture of its vulnerability to flooding. These profiles are classified into 5 categories according to their slope as given in Table 3. Then, one representative profile of each category is selected and studied for its resilience to flooding.

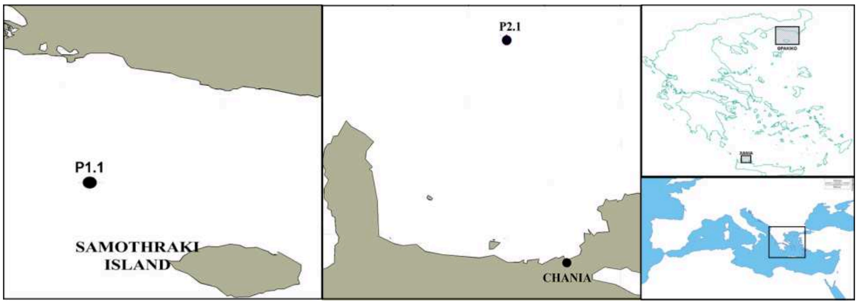

Figure 2. Study areas and grid points for wave data (Thrace (left) and Chania (right)).

3.1 *Area of Thrace*

The area of Thrace is located at the NE part of Aegean Sea and is about 150 km long. However, the region between Vistonida Lake and Agios Charalampos small port is studied (Fig. 2). A total length of 40km coast comprises a large variety of coastal types, such as small bays, cliffs, long straight beaches and estuaries. At the west part of the study area there are many small coastal lagoons, while the east part is characterized by several small estuaries. The dominant activity of the area is tourism, but there are more secondary socio-economic activities such as agriculture and residential development.

For the purposes of this work, 38 cross-shore profiles are created for describing the morphology of the area. As mentioned above, they are classified into five groups and a representative profile of each group was studied. The average slope of the coast is about 10.9% with milder slopes located at west part and steeper ones located at the east part of the study area. Beach/berm height varies between 0.5m and 6 m.

3.2 *Area of Chania*

The area of Chania is a coastline about 30km long, located at NW part of Crete Island (Fig. 2). The west part stretches 20km west of Chania city and is formed by long sandy beaches, while the east part is approximately 10km long and is formed by small embayed ones. The area of study is of high economic value because of the dominant activities, which is tourism and residential development.

For this study, 40 cross-shore profiles are selected for the complete description of the topography. They are grouped into five categories according to their slope and five representative profiles are studied. The average slope is about 10% and the range is between 3% and 19%. Beach/berm height varies between 0.4m and 5m.

4 WAVE DATA

4.1 *Present and future wave climate*

A third-generation spectral wave model (SWAN) is used to simulate present (1951-1999) and future wave climate (2000-2049, 2050-2099) at regional scale. A high resolution (0.005x0.005 degrees) simulation is performed, one for each area and their Longitude and Latitude boundaries of each coastline are presented in Table 1 (Krestenitis et al., 2013). The output results of SWAN model have a time step of 3 hours (H_s, T_p and wave direction).

The climatic wind data used for the wave simulations are produced in the context of the CCSEAWAVS project, using the ICTP RegCM3 model (Dickinson et al. 1989) with spatial resolution of 10x10km and temporal resolution of 6 hours (wind speed and direction were considered 10m above sea surface). RegCM3 is forced by the A1B SRES emission scenario of IPCC (Vagenas, 2014).

Table 1. Longitude-Latitude boundaries of each study area

	Longitude (deg)	Latitude (deg)
Thrace	[25.15-26.10]	[40.30-41.05]
Chania	[23.75-24.15]	[35.50-35.80]

The bathymetric data sources used for SWAN simulations consist of: (a) The General Bathymetric Chart of the Oceans database (GEBCO), (b) Nautical charts from the Hellenic Navy Hydrographic Service (c) The Global Self-consistent, Hierarchical, High-resolution Shoreline Database, used as zero depth reference.

Simulation results provide wave data for many grid points. In order to reduce the computational cost, representative points are selected for each area, after a homogeneity analysis (Galiatsatou, 2014). Finally, after evaluating the results of this procedure, one grid point for each study area is selected (P1.1 for the area of Thrace and P2.1 for the area of Chania, Fig.2) for the determination of the wave and storm surge characteristics of each region.

4.2 *Present and future storm surges*

For the simulation of present (1951-1999) and future (2000-2049, 2050-2099) storm surges a 2-dimensional hydrodynamic model MeCSM is used with spatial analysis of 10x10km and time step of 6 hours. MeCSM is forced by wind and pressure data, which were provided by RegCM3 simulations for the A1B SRES emission scenario of IPCC and have a spatial resolution of 10x10km and a temporal resolution of 6 hours (Vagenas, 2014).

5 ANALYSIS OF RESULTS

As analyzed above, two methodologies are followed for the study of the vulnerability to flooding of the two areas. The minimum H_s used for the definition of the storms is set to 1,5m for the area of Thrace and 2.5 for Chania. The waves with the proper direction for each coastal region (SW to SE for Thrace and NE to NW for Chania) are taken into account for the analysis. The evaluation of vulnerability to flooding is estimated for 5 representative cross-shore profiles selected from each area according to their slope.

5.1 *1st Approach*

All storms and their characteristics (E, maximum H_s and duration) are extracted from the corresponding time series using MATLAB™ software. Average values of the data for storms of each class are presented in Table 2.

Table 2. Average values of storm data for each class for the two study areas.

Grid Points	Storm	1951-1999					2000-2049					2050-2099				
(Coordinates)	Class	St*	D (h)	H_s (m)	EC (m^2h)	ξ (m)	St	D (h)	H_s (m)	EC (m^2h)	ξ (m)	St	D (h)	H_s (m)	EC (m^2h)	ξ (m)
	1	25	13	1.8	21	0.14	64	16	2.0	32	0.14	40	14	1.8	23	0.13
Thrace	2	37	22	2.1	46	0.14	17	35	2.6	79	0.14	33	26	2.3	58	0.14
P1.1	3	9	32	2.5	85	0.14	3	44	3.1	148	0.15	10	40	2.7	134	0.15
(25.30°-40.65°)	4	6	47	2.6	146	0.12	4	51	2.9	208	0.10	3	60	3.1	287	0.01
	5	4	41	3.0	245	0.14	1	60	3.4	445	0.14	1	138	3.2	559	0.16
	1	396	15	2.9	103	0.09	320	13	2.9	85	0.09	435	14	2.9	99	0.07
Chania	2	203	36	3.6	343	0.09	202	29	3.4	244	0.09	223	36	3.4	310	0.07
P2.1	3	80	64	4.3	772	0.10	188	51	3.9	535	0.09	117	60	4.0	673	0.08
(23.95°-35.80°)	4	10	93	5.0	1467	0.14	33	86	4.8	1167	0.11	33	99	4.8	1337	0.10
	5	8	114	6.1	2045	0.11	6	117	5.5	2084	0.12	3	135	6.9	2913	0.10

* Number of storms

For the area of Thrace it can clearly be seen that for future climate conditions, higher values of H_s are estimated. More specific, for the fifth storm class which is the most dangerous for the coast, an increase of 0.4m (13%) is estimated for the period 2000-2049, while the increase is lower (7%) for 2050-2099. All average H_s values for present and future climate conditions range from 1.8m to 3.4m. The results also highlight storms with longer duration for the future climate for all classes. The average duration of the fifth class storms increases by 80% for the second time period and reached 130% for the third period.

On the contrary, for the area of Chania all values of H_s are shown to decrease (for storm class 5 this decrease was 0,6m (10%) for the second time period. For the last 50 years (2050-2099) H_s slightly decreases for the first four classes compared with that of the present conditions, while there is an increase for the 5^{th} class of 0,8 m (13%). With regards to the area of Thrace, all averaged values of H_s for the area of Chania are almost doubled. This is due to the area topography (non-sheltered area) and the Etesian wind forcing of the coast. Storm duration appears to have lower values for all classes of the 2^{nd} time period, except for the fifth class where there is a small increase of 3%. For the 3^{rd} period, the results showed an increase of 18%. It has to be stressed that for future climate conditions there are less storm events of high energy (class 5) than the present ones.

The last step is the calculation of the FVI for each representative profile of each class. Considering the aforementioned wave and storm surge data (Table 2) and including the variable of the beach characterizing its ability to cope with each process (B, Table 3), FVI was calculated.

Table 3. Vulnerability to flooding for 5 representative profiles of each site.

Time period	B	Slope	Profile	%	1951-1999		2000-2049		2050-2099	
Storm Class	(m)	%	Category		4	5	4	5	4	5
Thr-Prof1*	1.5	3.8	I	19	L**	M	L	M	M	M
Thr-Prof2	1.7	5.4	II	26	L	M	M	M	M	M
Thr-Prof3	1.7	6.3	III	10	L	M	M	H	H	H
Thr-Prof4	2.0	9.4	IV	16	M	H	H	VH	VH	VH
Thr-Prof5	2.8	13.3	V	29	M	H	H	H	H	H
Ch-Prof1	0.4	2.9	I	5	VH	VH	VH	VH	VH	VH
Ch -Prof2	1.1	5.5	II	5	VH	VH	VH	VH	VH	VH
Ch -Prof3	2.6	6.8	III	18	M	H	M	H	M	VH
Ch -Prof4	2.8	9.3	IV	20	H	VH	H	VH	VH	VH
Ch -Prof5	3.5	13.0	V	52	VH	VH	VH	VH	VH	VH

* Thr=Thrace - Ch=Chania
** L=Low-M=Medium-H=high-VH=Very High

From Table 3 it is obvious that high coastal vulnerability to flooding is predicted for the area of Chania where all 5 representative profiles appear to have high or very high vulnerability for category 5 storms. In contrary, for the area of Thrace and present wave climate only 2 profiles, representing the 45% of the coast, appear to have high vulnerability to flooding, while for future conditions this percentage of profiles with high or very high vulnerability raises to 55%.

5.2 *2^{nd} Approach*

The maximum storm of each year (maximum H_s) is selected using MATLAB™ and Ru is calculated for present and future conditions and for all 10 representative profiles (5 for each area). The annual maximum H_s is shown on Fig.3 for both Thrace and Chania. It is observed that H_s is significantly higher in Chania than that of Thrace.

The next step is to model the annual maximum Ru and ξ using a univariate generalized extreme value (GEV) distribution function. The return levels extracted using the GEV distribution function corresponds to return periods of 50, 100 and 500 years.

The results from maximum likelihood estimation of Ru for the area of Thrace are shown in Fig. 4. It can be seen that extreme values of Ru are decreasing for the future conditions, but still their values are

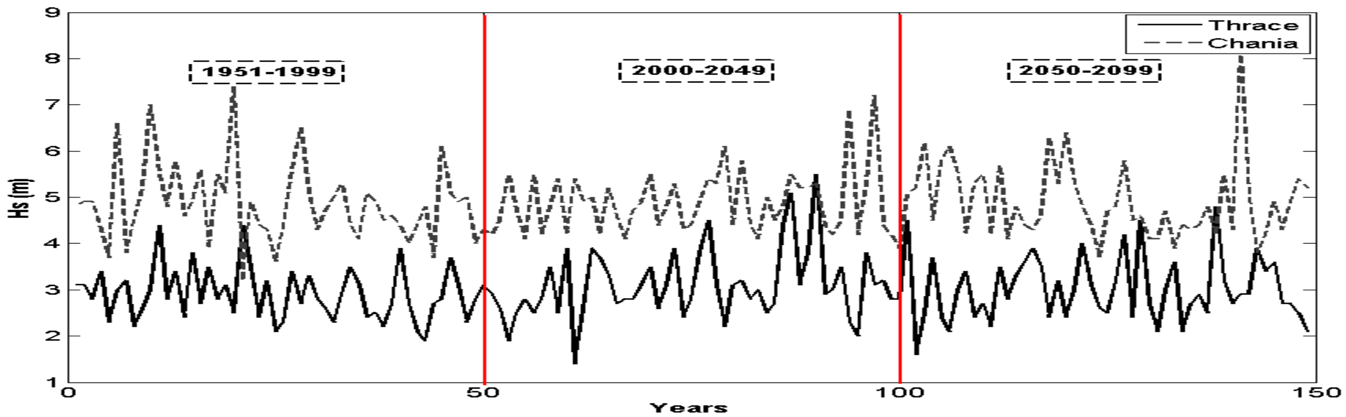

Figure 3. Maximum H_s per year for future and present climate conditions.

higher in comparison with the beach heights of the area (Table 3). In addition, the extreme values of storm surge are significantly high. For the return period of 50 years ξ is 0.39m for the present conditions, while for the future ones is 0.47(20% increase) and 0.41(5% increase), respectively.

For the area of Chania there were small differences of extreme Ru between the present and future wave climate conditions (2%), for the 5 profiles. The values of the Ru were high enough to overcome the beach height in any case. The storm surge predicted from the extreme value analysis is high enough to affect the total water level. For the return period of 50 years ξ is 0.36m for the present conditions, while for the future ones is 0.39 m (8% increase) and 0.32 m (11% decrease), respectively.

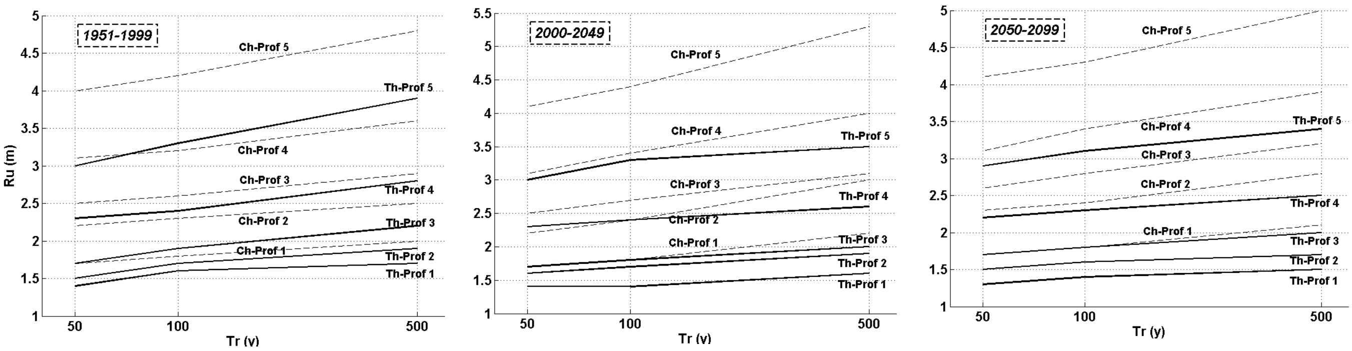

Figure 4. Maximum Likelihood Estimate of Ru for return period (Tr) 50, 100 500 years (Thrace=solid line, Chania=dashed line).

All FVI values evaluated for the representative cross-shore profiles were shown to be higher than 1 in every case, which corresponds to very high vulnerability. The predictions suggest that both areas are vulnerable to extreme waves and water level with return period of more than 50 years.

6 CONCLUSIONS

In this work coastal flooding vulnerability is estimated through the evaluation of the FVI, based on run-up and storm surge computations for both present and future climate. For this purpose two different methodologies are proposed and applied to two regions of Aegean Sea.

Using the first approach, average values of Ru and ξ of each storm class are estimated. The results show that the most vulnerable area is the site of Chania for both present and future conditions. The area has high values of berm height (2.6-3.5 m), with beach profiles 3, 4 and 5 representing 90% of the coast, and the Ru and ξ are also high, resulting in a Flood Vulnerability greater than one (High Vulnerability). On the other hand, the area of Thrace is forced by lower H_s (in comparison to that of Chania) and has relatively high values of berm height (1.7-2.8 m). Thus, it appears to be less vulnerable. The most vulnerable part of the region is the western part, with mild slopes and low berm heights. Future wave climate conditions seem to affect the coast by raising the FVI by one level. It should be noted that the storm surge ξ, used in the computations, is the concurrent with the H_s maximum of each storm. This results in low values of ξ ranging between 0.7 m and 0.14 m. It corresponds only to 5-10% of run-up for the area of Thrace and even lower for the area of Chania. So, it is clear that ξ does not remarkably affect the total water level.

The second approach, based on extreme run up and storm surge with return periods of 50, 100 and 500 years, indicate that both areas are very prone to flooding. The values of Ru, corresponding to each return period, estimated for the two areas, are shown to be significantly higher in comparison to beach height, while the tendencies are similar for the future climate (a small increase of 5% is observed). Extreme ξ values are also high, ranging between 0.35 - 0.53m. They correspond approximately to 16-20% of Ru (profiles 1-3) and to 10-12% (profiles 4 and 5) for the area of Chania, while for the area of Thrace the percentage ranges between 25-35% of the Ru for the first 3 representative profiles and between 15-20% for the profiles 4 and 5. Thus, it can be seen that it greatly affects the total water level.

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NOTATION

ξ	storm surge (m)
B	berm/beach height (m)
E	energy content (m^2h)
FIP	flood intermediate parameter
FVI	flood vulnerability index
H_s	significant wave height (m)
L_o	deepwater wave length (m)
Ru	run-up (m)
$tan\beta$	beach face slope
T_p	wave peak period (sec)

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