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Geomorphic coastal vulnerability to storms in microtidal fetch-limited environments: application to NW Mediterranean & N Adriatic Seas

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ABSTRACT

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A methodology to compare in relative terms the coastal vulnerability to storm impacts is presented and applied to three sites in the Mediterranean Sea. The analysis separately evaluates the vulnerability to storm-induced processes (inundation and erosion) and, it quantifies the contribution of the forcing (storm properties) and receptor (beach geomorphology) to the overall vulnerability. Beach geomorphology affects calculated vulnerability by influencing process intensity and the ability of the beach to cope with the impacts (resilience). Results showed that regarding wave-induced inundation, the highest vulnerable area is the Ebro delta (Catalan coast) due to a combination of storm properties and the existence of a very low-lying profile. On the other hand, when considering the storm-induced erosion, Lido di Dante (Italy) is the highest vulnerable area because despite the fact that the estimated erosion is not the largest one, the beach width is narrower than in the other sites. In any case, actual beach width at the three sites exceeds the estimated shoreline retreat. According to the obtained results the main induced process affecting coastal vulnerability is inundation.

ADDITIONAL INDEX WORDS: *Inundation, erosion, runup*

INTRODUCTION

Coastal vulnerability to storms can be simply defined as the potential of a coastal stretch to be harmed by the impact of a storm. In spite of this simple definition, there is not a single way of evaluation, with existing methods ranging from simple indices including basic geomorphic characteristics to detailed quantifications of the coastal response. In many cases, these methods have been developed for specific cases that make them hardly exportable to other sites. When referring to the geomorphic component, this vulnerability accounts for the modification of the coastal substrate (morphodynamic response to the storm) supporting socio-economic and environmental values. This will serve to managers to assess the expected magnitude of damages along the coast due to storm hazards to take (informed) decisions on mitigation/adaptation strategies.

As the magnitude of the coastal response to storms depends on both the magnitude of the forcing (storm properties) and characteristics of the receptor (coastal geomorphology), we assume vulnerability as being composed by two components associated to each factor (forcing and receptor). This approach permits to discriminate for any coastal site which is the main contribution to the overall vulnerability and, in consequence, to provide managers with information on which should be the main factor to be modified if coastal vulnerability has to be managed.

Within this context, the main aim of this work, we comparatively assess the vulnerability to storm impacts of three coastal areas representative of microtidal and fetch-restricted environments located in the NW Mediterranean and N Adriatic Sea. Here we evaluate the coastal vulnerability to storms by separately considering two induced processes: inundation and erosion (see *e.g.* MENDOZA and JIMÉNEZ, 2008).

AREA OF STUDY

The coastal vulnerability assessment is performed in three sites representative of microtidal and fetch restricted environments: the Ebro Delta (Catalan coast, Spain) , the Lido de Sète beach (Sète, France) in the NW Mediterranean and the Lido di Dante beach (Emilia Romagna coast, Italy) in the N Adriatic (figure 1).

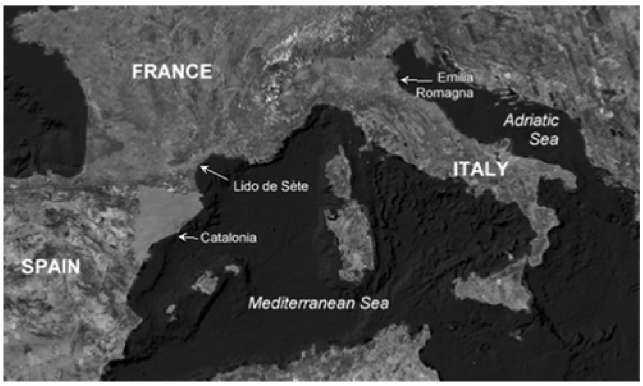

Figure 1. Area of study (Photo courtesy of Google Earth™).

These sites are characterized by the existence of dissipative beaches composed by fine sands (a common grain size could be used to represent local sediments, with d_{50} = 0.250 mm). Averaged beach slopes range from 0.028 in the Italian case to 0.042 and 0.048 in the Catalan and French coasts respectively. Surf zone slopes are typical of dissipative beaches and they are around 0.02. Beach heights are relatively low, being the Ebro delta the lowest due to the absence of any dune on the back of the beach. The average height of the selected area is 1.2, with a maximum value of 1.7 m. Along the French and Italian sites there is a dune ridge on the back of the beach with average heights of 3 m and 2.6 m respectively.

Figure 2 shows the wave height extreme probability function obtained for the three sites by using local wave data. Used wave time series are of different length and obtained wave climate can be considered as representative of the local values up to a return period, T_R, of 50 years in the French and Italian cases (due to the length of the used time series) whereas for the Spanish case they are valid up to 150 years. As it can be seen, wave heights associated to any T_R are almost equal in the Spanish and Italian case, whereas the corresponding value in the French coast is significantly higher.

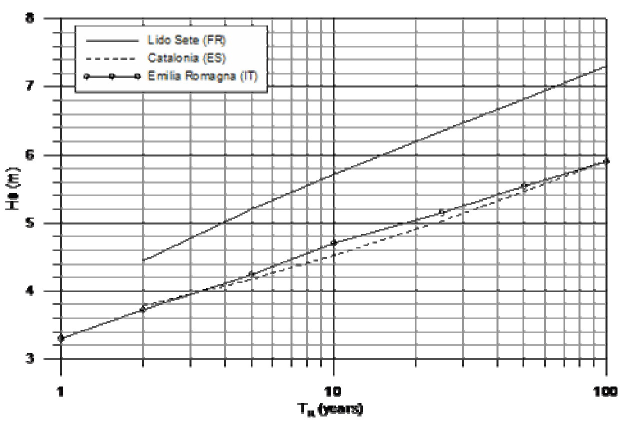

Figure 2. Wave height extreme distributions at the study areas.

In addition to this, we obtained the relationship between the remaining parameters characterizing storm properties (wave peak period, *Tp*, and storm duration, τ) with *Hs*. With these relationships we can reconstruct the full characteristics of a storm associated to any return period.

A description on study site characteristics including wave climate can be found in CERTAIN and BARUSSEAU (2005), JIMÉNEZ *et al*. (1997) and ARMAROLI *et al* (2005) among others.

COASTAL VULNERABILITY ASSESSMENT

Generalities

To comparatively assess the geomorphic vulnerability of the three sites we have analyzed separately the component of the vulnerability associated to the forcing (the storm) and to the receptor (the coast). Finally, they have been integrated into a vulnerability index to assess the overall vulnerability at each site.

One of the main questions regarding vulnerability assessments to storms is to decide which will be the event to be used in the analysis. This selection will severely control the results since the longer the T_R is, the larger the response will be and, consequently, (potentially) also the vulnerability will be. In this work we have (arbitrarily) selected a T_R = 50 years as the base event to calculate the coastal vulnerability. To get a guess of the relevance of the selected T_R, table 1 shows the probability of exceedence of such event to be equaled or exceeded during some time periods.

Table 1: Probability of occurrence of a 50 year T_R event for different time periods.

Time period (years)	Probability (%)
2	3.96
5	9.61
10	18.29
25	39.65

As it was mentioned above, the vulnerability is separately calculated for the two storm-induced processes: inundation and erosion. In this paper, we consider that storm-induced inundation is mainly driven by wave action, i.e. it is defined by the run-up at the peak of the storm. Here we calculate it by using the $Ru_{2\%}$ formula proposed by STOCKDON *et al* (2006). To calculate the storm-induced erosion we follow the approach proposed by MENDOZA AND JIMÉNEZ (2006) where beach profile erosion is calculated by using both the *Sbeach* model (LARSON and KRAUS, 1989; WISE *et al*. 1996) and a parametric way in function of storm and beach profile parameters (Hs, Tp, τ, w_f, $tan\beta$).

Vulnerability component associated to the forcing

To calculate the component of the vulnerability associated to the forcing, we have used two intermediate parameters only accounting the wave induced contribution to each process.

Taking into account the dependence of $Ru_{2\%}$ with wave variables, the used parameter to characterize inundability, *IN*, is given by

$$IN \propto \sqrt{(H_s L_o)} \quad (1)$$

Following MENDOZA and JIMÉNEZ (2006), beach profile erodibility due to storm impact, *ER*, is proportional to an excess of the Dean's parameter, D (= $H / w_f T$), above an equilibrium value,

$$ER \propto \left(\left| D - D_{eq} \right|^{0.5} \tan\beta \right) \tau \quad (2)$$

To only account differences associated to wave climate, *ER* is evaluated assuming that the beach profile at the three sites is the same, being characterized by a d_{50} = 0.25 mm and a $tan\beta$ = 0.05.

Figure 3 shows the comparison of the vulnerability to inundation for the three sites associated to storm properties. Curves are presented in relative terms with respect to the maximum calculated *IN* value associated to the reference T_R (50 years). As it can be seen, the highest vulnerability in terms of inundation corresponds to the Catalan coast whereas storms in the Adriatic present the lowest associated potential values. This is due to the fact that recorded T_p during storms off Catalonia are the longest ones and, this variable dominates over *Hs* in wave runup calculations (see equation 1).

To illustrate the differences found between the three sites, table 2 shows the T_R associated to a given storm inducing the same potential vulnerability at each site. Thus, for instance, to induce the same vulnerability to inundation associated to the impact of a storm with a T_R of 27 years in the Catalan coast, a storm with a T_R of 50 years should be required in Lido de Sète and with a T_R longer than 100 years in the Italian case.

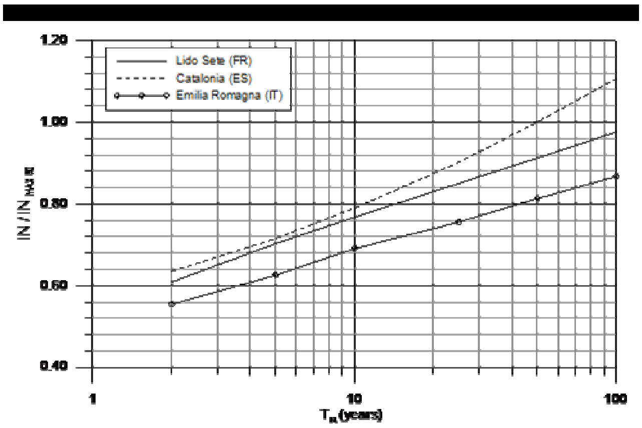

Figure 3. Ratio of the vulnerability to inundation associated to storm properties at each site with respect to the maximum value at the reference T_R (50 years).

These values clearly indicate that unless the coastal geomorphology at each site will modulate/modify the induced vulnerability, the Catalan coast should be the most vulnerable coast to storm-induced inundation. In addition to this, it has to be considered that differences in storm surge regimes at the three sites could alter this result because the obtained assessment only includes the wave induced part.

Figure 4 shows the comparison of the vulnerability to erosion for the three sites associated to storm properties. As in the previous case, curves are presented in relative terms with respect to the maximum calculated *ER* value associated to the reference T_R (50 years). In this case, the highest vulnerability in terms of beach erosion corresponds to the French coast whereas storms in the Catalan coast present the lowest associated potential values although very similar to the obtained for the Italian coast. In any case, the estimated difference in the response between sites is smaller than the obtained for inundation. This is clearly seen in Table 2 where the comparison of required storms to induce the same vulnerability along the three sites is presented.

Thus, to induce the same vulnerability to erosion associated to the impact of a storm with a T_R of 50 years in the French coast, a storm with a T_R of 67 and 65 years should be required at the Spanish and Italian cases.

Table 2: Storms defined in terms of T_R required to induce the same vulnerability to inundation and erosion at each site.

process	Catalonia (ES)	Lido de Sète (FR)	Emil.- Romag. (IT)
Inundat.	50	> 100	>> 100
	27	50	> 100
	12	17	50
erosion	50	35	46
	67	50	65
	53	38	50

Vulnerability component associated to the receptor

Once the component of the vulnerability associated to the wave climate was evaluated, a similar analysis to account for the contribution of the receptor's characteristics (coastal geomorphology) to the overall vulnerability was performed. The modulation of calculated vulnerability due to beach characteristics is done at two levels: first, the profile shape and sediment grain size will condition the magnitude of the response (smaller erosion

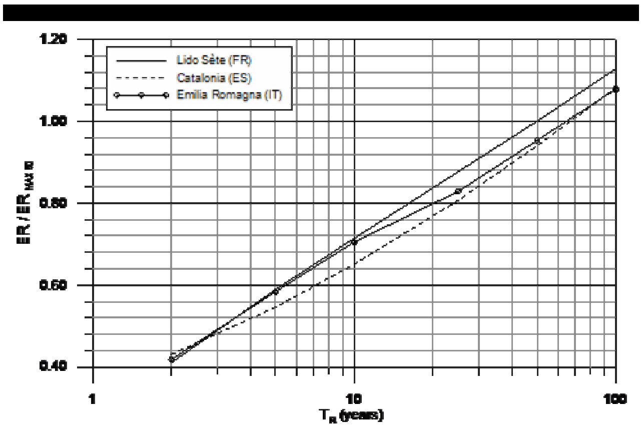

Figure 4. Ratio of the vulnerability to erosion associated to storm properties at each site with respect to the maximum value at the reference T_R (50 years).

and smaller runup for more dissipative profiles) and, second, the dimensions of the profile will determine their "resilience" (e.g. higher profiles will have a lower probability to be inundated). Due to this, the introduction of the effect of the receptor's characteristics will be done in two consecutive phases: first by estimating the effects on the magnitude of the induced process and, second, by estimating the effects on the overall response.

As in the previous case, the analysis is separately done for inundation and erosion and, again, results are presented in relative terms with respect to the maximum calculated for T_R = 50 years.

Figure 5 shows the vulnerability calculated for inundation when beach properties are also accounted for. In this case, instead of using equation (1) that only includes the wave-related part of the runup model, we used the full predictive runup formula which in practical terms means to assess the additional effect of the beach slope in the before mentioned calculations.

As it can be seen, when including local beach characteristics, the estimated vulnerability to inundation of the three sites differ from the previously presented one (figure 3). Thus, although the Italian site is again the lowest vulnerable to inundation, the estimated difference with respect to the other sites is larger. This is because it presents the mildest beach slopes and, in consequence, the wave induced runup will be the smallest. To put these results in the adequate context, it has to be considered that we are only accounting for the wave contribution to inundation and, the local storm surge regime (marginal and/or jointly with waves) could significantly modify this vulnerability.

The estimated vulnerabilities for the Spanish and French sites have the same magnitude (figure 5). This is because beach slopes in Lido de Sète are steeper than in the coastal stretch analyzed in the Ebro delta (Catalan coast). Thus, the above calculated difference in inundability for these sites just based on wave climates (figure 3) is strongly modified by the local coastal geomorphology. Just to put in context these results, it has to be considered that along the Catalan coast beach profiles range from dissipative to reflective ones. Of course, when estimating the vulnerability to inundation for reflective beaches, the calculated value drastically increases as the beach slope does.

The vulnerabilities to erosion assessed for each site in relative terms when beach properties are also accounted can be seen in figure 6. In this case, equation (2) is fully employed by including a representative (averaged) value of beach (surf zone) slope of each site. As occurred with inundation, these results significantly differ from those obtained by only using storm properties (figure 4).

Although the French site is again the highest vulnerable to erosion, the difference in magnitude with respect to the other sites is much larger. This is because this area is characterized by the largest inner surf zone slope (in average) and, in consequence, erosion will be much larger. The lowest calculated vulnerability for the Catalan case is due to the fact that beach profiles of the analyzed coastal stretch (Ebro delta) are very dissipative and, although wave climate should potentially be able to induce significant erosion, a large part of wave energy will be efficiently dissipated in the surf zone. As it was previously mentioned, if reflective beaches should be selected to make the analysis in the Catalan coast (they dominate in some parts of the coast), results will be significantly different and, the largest induced erosion should be expected.

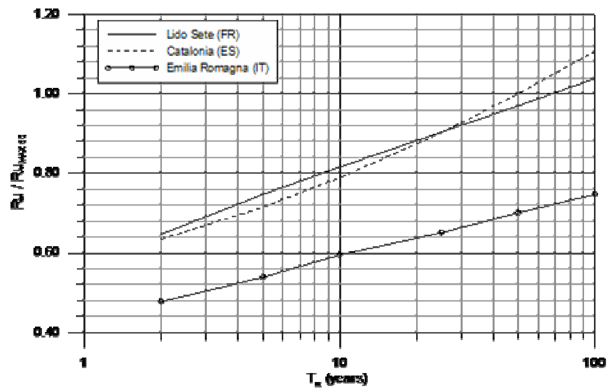

Figure 5. Ratio of the vulnerability to inundation associated to storm properties and beach morphology at each site with respect to the maximum value at the reference T_R (50 years).

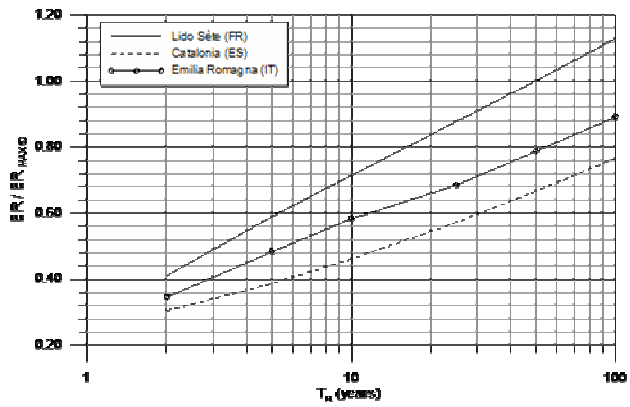

Figure 6. Ratio of the vulnerability to erosion associated to storm properties and beach morphology at each site with respect to the maximum value at the reference T_R (50 years).

Finally, to estimate the total vulnerability to each process at each site, an index including the variable of the beach characterizing the ability to cope with each process (an indicator of the beach resilience) was calculated. To compare the results in simple terms, this indicator is a simplified version of the used ones by MENDOZA and JIMÉNEZ (2008) and they are given for inundation, *V_I*, and erosion, *V_E*, respectively by

$$V\_I = Ru / Z \quad (3)$$

$$V\_E = \Delta x / W \quad (4)$$

where Z is the beach/dune height, Δx is the induced shoreline erosion and W is beach width.

In the case of inundation, the index *V_I* represents a measure of the relative dimension of the maximum water level at the beach (which in this case is just given by the wave-induced runup, *Ru*) with respect to the maximum elevation of the beach. Thus, for coasts characterized by a high inundability (determined both by wave climate and beach slope), the presence of a dune or a dike will significantly reduce its vulnerability. Figure 7 shows the calculated values for this vulnerability index at the three sites in relative terms. Values are normalized with respect to the maximum value associated to the reference storm (T_R = 50 years).

As it can be clearly seen, the introduction of the geomorphological variable characterizing the ability to cope with inundation fully conditions and changes the previous estimated comparisons (figures 3 and 5). Obtained results show that the highest vulnerable area to inundability due to storm impacts is the Catalan coast (the Ebro delta in this case). This huge difference with respect to the other two sites is because this area can be classified as a very low-lying environment, whereas the French and the Italian sites are characterized by the presence of a dune row along the back of the beach. In fact, whereas *Ru/Z* values for any storm are larger than 1 in the case of the Catalan coast (all induced runups exceed the beach height and the coast should be potentially inundated), in the case of the French and Italian cases, *Ru/Z* values are ever below unity, indicating that reached water level is lower than dune elevation (in average along the beach, although there are some few locations along each coast where local values can exceed the beach height).

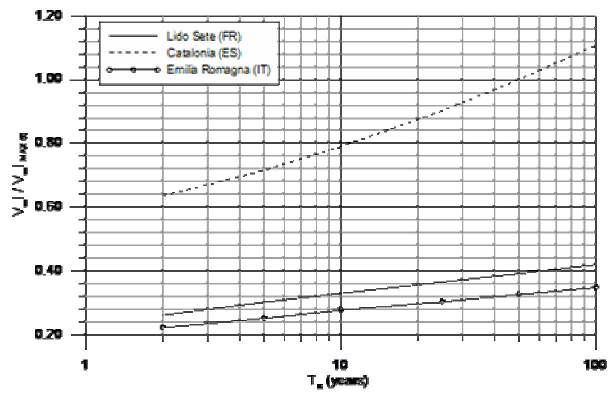

Figure 7. Ratio of the vulnerability to inundation at each site with respect to the maximum value at the reference T_R (50 years).

In the case of erosion, the index *V_E* represents a measure of the relative dimension of the storm-induced shoreline retreat with respect to the actual beach width. Thus, for coasts characterized by a high erodibility (determined both by wave climate and beach characteristics), the existence of a wide beach will significantly reduce its vulnerability. In some cases, this vulnerability can be even zero if existing uses and resources are not affected by the storm. To incorporate the effect of the beach width, instead of characterizing the erosion potential (equation 2), we directly evaluate the storm-induced erosion in each profile by using the Sbeach model. Figure 8 shows an example of the obtained results for one representative profile of Lido de Sète (France) under the impact of different storms.

Figure 9 shows the calculated erosion vulnerability, *V_E*, values at the three sites normalized with respect to the maximum value associated to the reference storm (T_R = 50 y). In this case, the introduction of the beach width as characteristic variable of the ability to cope with erosion also modifies the previous estimated comparisons (figures 4 and 6). Results show that the highest vulnerable area to erosion due to storm impacts is the Italian coast. This increase in relative vulnerability with respect to the other sites is because beach width in this area is thinner than in the other two sites. In any case, these values are just indicating the relative values between sites because if we focus in absolute values for each site, all the calculated *Δx/W* values for any storm are smaller than 1. This means that under ideal conditions (beach width not affected by other processes), beach configurations will be able to cope with storm-induced erosion (in average terms). The lowest values calculated for the Catalan case are due to the fact that the potential vulnerability is the lowest (due to the combination of storm properties and beach characteristics) and that the local beach is very wide. In any case, the vulnerability to erosion has been calculated for average widths and, it is possible to find coastal stretches with smaller local values. As an example, values obtained for the French site only comprise the northern part where the beach is the narrowest. If overall width values along the barrier were used, the relative vulnerability should decrease because the beach width in the southern part increases between 4 to 7 times.

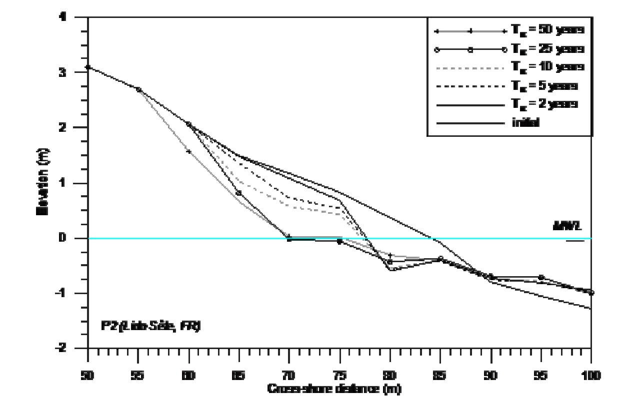

Figure 8. Example of simulated beach profile erosion due to the impact of storms associated to different T_R at the French site (only a zoom of the inner part of the beach is showed).

CONCLUSIONS

A comparative vulnerability assessment to storms in three sites of the Mediterranean has been done. The analysis separately evaluates the vulnerability to storm-induced processes (inundation and erosion) and, quantifies the contribution to the estimated vulnerability of the forcing (storm properties) and receptor (beach geomorphology). This last one accounts for geomorphologic influence on the process's intensity and on the beach resilience. Results showed that regarding wave-induced inundation, the highest vulnerable area is the Ebro delta (Catalan coast) due to a combination of storm properties and the existence of a very low-lying profile. On the other hand, when considering the storm-induced erosion, Lido di Dante (Italy) is the highest vulnerable area because although the estimated erosion is not the largest one the beach width is narrower than in the other sites. In any case, actual beach width at the three sites exceeds the estimated shoreline retreat due to storm impacts.

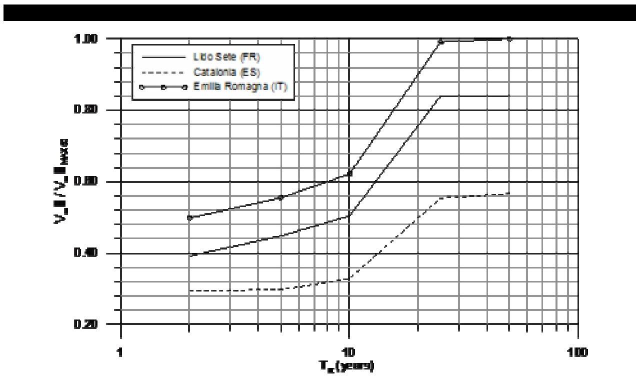

Figure 9. Ratio of the vulnerability to erosion at each site with respect to the maximum value at the reference T_R (50 y).

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