Answer to Editor's comments after first review

Editor Comments

AA: Authors' Answers

Dear authors,
thank you very much for your response to the 2 reviews. As you have seen, both referees find your work valuable, however, both also have a number of comments and concerns. In particular, reviewer #1 questions the use of BNs in the context of your study. I feel that this is a fundamental point, as he/she argues to have experience with BNs, but still does not see its justification.
I decided on 'major revision', but my understanding is that this fundamental issue needs to be completely resolved before the work could be considered for publication. Major concerns about the appropriateness of the applied method would lead to rejection of the paper. Related to this fundamental issue is the question of the scientific contribution of the paper which was not completely clear to me.
One formal issue: Could you please clearly mark your answers to the comments in the response letter? For example, for some comments, your response follows directly to the comment without sign (AA).
Best regards, Bruno Merz

Dear Editor,

In what follow we address all questions and concerns raised by reviewers. In all the cases we include the original reviewer's comment after the sign (RC) followed by our response after the sign (AA).

The main change in the manuscript is a reduction of the Results section and the integration of the Discussion in a single section without subsection for the study sites. Nonetheless, the whole document has been thoroughly reviewed and edited to answer to the requirements and suggestions of the reviewers, enhancing a clearer interpretation of our work.

Answer to #1 referee's review

RC0: #### general comments

The authors present a risk assessment for coastal storm impacts to support decisions on disaster risk reductions. For that purpose, a Bayesian network approach is used to link process-oriented models, that predict the hazards at the receptors, with vulnerability relations to obtain the final expected impact. In a case study two Mediterranean sandy coasts are considered.

The paper is well structured and provides a well-argued motivation and problem definition. Further the study areas are described in detail and underline the relevance of the presented study. Despite a good structure in the Methodology section, some aspects of the method remain unclear to me, which might be due to the complexity of the model chain. This affects especially the Bayesian network (BNs) application. Even though I am familiar with the construction and application of BNs, I have problems to follow the construction (i.e. parameter setting) of the BNs and to understand the motivation for and advantages of using BNs in the presented context. The results section provides an extensive analysis of different climate change and adaptation scenarios for the considered Mediterranean coasts. Yet, I did not understand which storm intensities are considered here (this might be due to a missing understanding of the methodology).

The discussion names several aspects that pose challenges or are neglected in the presented model approach and might consequently be taggled in follow up studies. Yet, to my impression important critical points of the presented approach are missing, as will be specified in the specific comments.

AA: Thanks for comments and suggestions on submitted manuscript. In what follows we answer to all comments/suggestions/questions raised by the reviewer.

RC1: #### specific comments

I found it quite difficult to keep track of all abbreviations used in the paper.

AA: We understand that the use of a large number of abbreviations could be cumbersome, especially for a long text as this manuscript is. We have reviewed the text and reduced the number of abbreviations to a minimum.

abstract:

RC2: line 15: "a large number of storm characteristics" What is a large number? To my understanding 3-4 storm characteristics were considered.

AA: When we mention “storm characteristics” we refer to storms defined in terms of a combination of Hs, duration, direction and water level. In each site, we have selected 12 storms for each sea level rise scenario, i.e. 24 storm combinations per site. This is later specified in the text (including table 1). Additionally, each storm combination is represented by 2 different simulations where storm variables are slightly changed within the range corresponding to its category. We have modified this sentence in the abstract by the following “*Process-oriented models are used to predict hazards at the receptor scale which are converted into impacts through vulnerability relations. In each site, a total of 48 storms have been simulated under different scenarios and obtained results are integrated by using a Bayesian Network to link forcing characteristics with expected impacts through conditional probabilities.*”

RC3: line 17: "The tool has been proven successful in reproducing current coastal responses at both sites". I could not find any model verification in the paper. Only a reference to a paper that verifies a part of the model.

AA. In order to avoid confusion with morphodynamic model validation we have changed the sentence to “*Consultations with local stakeholders and experts have shown that the tool is valuable for communicating risks and the effects of risk reduction strategies. The tool can therefore be valuable support for coastal decision making.*”

Section 3.2:

RC4: page 7, line 7: The discretization of the variables is hardly motivated. What is the motivation for choosing 2 or 3 or n intervals for a certain variable? How are the interval boundaries selected (equidistant, equifrequent, entropy-based, ...)? How is the probable range determined (only so far observed values)? Some information about the distribution of these variables might help to motivate the discretization. What are the effects of discretizing? In the discussion it is mentioned that accuracy comes at computational costs, but this information is quite sparse (no information about number of intervals scales with computational costs or what are the computational costs of the current network for parameter determination and for inference).

AA: To avoid confusion in this section we remove "*Storm scenarios are defined […] were selected for use in the analysis*." (lines.6-9), since we already explain that storm scenarios are combinations of variable values covering the typical storm condition at each study site. The description of bins only makes sense in terms of the BN, which we have not explained yet in this section. Then we will motivate the discretisation of variables in section 3.6.1.

Thus, we have added in section 3.6.1 the following text: "*The bin ranges for variables characterising boundary conditions is selected to be equidistant covering the observed values at each study site (Table 1). Additional non-observed ranges are introduced to account for SLR. The used number of intervals is a compromise between accuracy and computational effort. Each combination showed in Table 1 has been simulated twice to account for potential variability inside bins. Then, all simulations are repeated for DRR scenarios affecting hazards (i.e. Winter Dune and Nourishment + Dune). Therefore, a total number of 96 model runs were required for the applied bin set-up. As a reference, using parallel simulations with 48 threads, the ratio computation time over real storm time was ~0.2, meaning that a 40 hr storm takes ~8 hours of simulation time.*"

RC5: page 7, line 12: "time series" of what?

AA. We have modified the sentence as "*In addition, time series of waves (either bulk Hs, Tp and mean direction or spectrum) and water levels during each storm event were used when this information was available.*".

RC6: page 7, line 19-20: the "(24 simulated storms)" confused me? Why do you consider 24simulated storms for 12 state combinations?

AA. See answers to comments 2 and 4. In addition to avoid confusion, the sentence is rephrased to avoid the brackets.

The new sentence is "*The selected bins for each variable can be seen in Table 1. These lead to 12 combinations defining the source under current MSL and 12 under future MSL (given by a*

SLR scenario). Each combination of states is simulated twice by means of slightly different storms to account for potential variability within variable ranges, leading to a total of 24 storms under the current MSL and 24 under SLR"

We have also changed Table 1 for better interpretation of variable discretization.

RC7: page 7, line 24: What are synthetic triangular events?

AA. It is the way to reproduce storm events not previously recorded to be used in the numerical model. To clarify this, we have included this text:

"*To include the full range of cases, the remaining eight storms were completed by using combinations of Hs-duration-direction not previously recorded. These events were modelled assuming they follow a triangular-shaped evolution with the peak intensity at the half of their duration (see e.g. McCall et al. 2010; Poelhekke et al., 2016).*"

RC8: page 7, line 27-28: "water level and Hs are uncorrelated" <- a reference is needed?

AA. The reference is (Mendoza and Jiménez, 2008) which was located at the end of the next sentence. We have rephrased to avoid confusion.

RC9: page 8, line 1: How are the driving variables identified? Why are the remaining variables considered to have no effects? How is the distribution of the storm defining variables defined? To my current understanding an equal amount of storms for each state combination is considered, which infers a uniform distribution of the variables. Yet, I would expect that small Hs values or smaller durations are more likely than higher values? Is this accounted for?

AA: Considered driving variables in the analysis have been selected taking into account storm characteristics at each site. Thus, in the Tordera Delta case, Tp does not significantly vary during storms so, we don't consider it a variable to be discretized. Moreover, storm surges play a secondary role in comparison with wave contribution to total water level. This now justified in the text with specific references describing storm conditions in the area: "*For the Tordera Delta case, the selected variables to define storm scenarios were Hs at the peak of the storm, total storm duration, and incoming storm direction. Tp does not significantly vary during storms in* *the study area (see Mendoza et al., 2011) and was not included as a characteristic variable. Due to the coastline configuration and morphology, the area is sensitive to storm incoming direction (Sanuy and Jiménez, n.d.). Thus, the main directions in terms of dominant (E) and secondary (S) storms needed to be considered separately. Finally, the position of the mean sea level (MSL) during the event was included to reproduce hypothetical future projections of sea level rise (SLR) due to climate change".*

This is also completed for the Italian case as:

"Previous works in the area of the Lido degli Estensi-Spina case study have identified the dominant role of wave height and total water level in controlling the magnitude of storm-induced erosion and inundation (Armaroli et al 2009, 2012). Due to this, variables used to characterize the source were the maximum Hs and maximum TWL (surge+tide) during each storm event. Thus, wave period and the direction of the storms was not considered as a source characteristic variable to be discretized. Each storm was simulated for current and climate change (SLR) scenarios. Finally, and similarly to the Tordera case study, each Hs-TWL combination was simulated twice to account for potential variability"

With respect to the distribution of the storm defining variables, it is true that the BN is trained with equal representation of all variable combinations. This implies that once the Bayesian is trained, the "prior" probabilities of storm variables are uniform. We have followed this approach because extreme value probability distributions of source variables are not known for the two sites and estimating them was beyond the scope of this study. In spite of this, once relative frequencies of different events are available, source nodes could be re-trained which will result in an automatic update of the distribution of all hazard and consequence nodes. Moreover, the user could also test how different assumptions on the source variable distributions would change the hazard and impact estimates. Nonetheless, the main strength of the BN at its current stage is that it enables decision makers to explore different scenarios and helps them to design robust strategies (i.e., strategies that are successful under most scenarios.). We have covered this point in Results and Discussion sections. See answers on comments on those sections.

Section 3.3:

RC10: Only one event (storm) is considered for each combination of states. Yet, similar events might result in different outcomes. Further, the applied model chain seems to provide deterministic results. Consequently, no uncertainties are considered/captured in the model construction. Since BNs are explicitly designed to capture uncertainties, I wonder why this approach was chosen here.

The distribution of hazard at the receptors results from the different location of the receptors, but does not reflect the uncertainty related to the inundation or erosion at a specific object. In a strict sense, I would not judge the resulting distribution to represent probabilities.

AA: We answer the comment in splitting it in different shorter pieces:

RC10.1: Only one event (storm) is considered for each combination of states. Yet, similar events might result in different outcomes.

AA. Two storms are simulated for each combination (we agree that this was not properly explained, see previous answers). Furthermore, the user could select storms belonging to for example Hs = 3-4 meters with waves coming from the East for current MSL but leaving the duration unconstrained as an uncertain variable. In such a case the obtained output would be the integrated result from 4 simulations (2 direction categories that are represented by 2 simulations each with different values of duration). Therefore, results will account for the uncertainty on duration for a given (certain) Hs. In practice, this could be relevant because storm forecasts could contain more certainty on some variables than on others, for example as a result of ensemble forecasts. For a more detailed discussion how the BN tool can deal with ensemble forecasts also see section 5 in Jäger et al. 2017. A Bayesian network approach for coastal risk analysis and decision making. Coastal Engineering (in press, 10.1016/j.coastaleng.2017.05.004).

RC10.2. Further, the applied model chain seems to provide deterministic results. Consequently, no uncertainties are considered/captured in the model construction.

AA. Reviewer is right, we do not account for uncertainties inherent to individual models. Quantifying uncertainties of individual models is another study in itself (e.g. Wagenaar et al. 2016. Uncertainty in flood damage estimates and its potential effect on investment decisions. NHESS, 16, 1-14), and it is beyond the scope of this manuscript to do such analysis.

RC10.3. Since BNs are explicitely designed to capture uncertainties, I wonder why this approach was chosen here.

AA. A BN can be a compact representation of a high-dimensional probability distribution. In this study, we used an existing BN approach and algorithm (Jäger et al. 2017.. Coastal Engineering, 10.1016/j.coastaleng.2017.05.004) to integrate high-dimensional data from various underlying models in a compact way. As mentioned in previous answers, the main purpose is to explore scenarios (forward prediction) or to gain insight in the main drivers of hazards and impacts (backward prediction).

RC10.4. The distribution of hazard at the receptors results from the different location of the receptors, but does not reflect the uncertainty related to the inundation or erosion at a specific object. In a strict sense, I would not judge the resulting distribution to represent probabilities.

AA. The most intuitive interpretation of the distribution of hazards and consequences at the receptors is indeed as the "expected fractions of receptors with the single hazard or impact levels". However, they could be interpreted as probability distributions for an arbitrarily selected receptor whose location is known. Nonetheless, we removed the following in the main text to not confuse the reader:

Page 2, lines 27 – 29 "This implies […] probabilistic-based analysis of the results."

Page 6, line 33: "probabilistic".

Conclusions, last sentence " and their uncertainties"

Section 3.4:

RC11. To model the consequences flood damage curves are applied. Those are generally related with huge uncertainties (a wide range of relative damage can be observed for equal water levels), which are again neglected and not included in the BN. On top, a damage curve that was derived for river flooding is applied. Since the process of storm surges is very different from river flooding the applicability should be discussed. In terms of risk levels, the values selected for both study sites differ significantly. E.g. medium impact building damage ranges from 0.26 to 0.45 compared to 0.1 - 0.2. Why are these intervals chosen?

AA. Ideally, damage curves have to be specifically built for local conditions (including associated uncertainty). However, in the study site, such information is not available and, official water management agencies recommend the use of a representative damage curve for flooding analysis. These are the selected curves used in this work (they are properly referenced). Now, we have stressed in the text the motivation and implications of the curves selection and the final risk levels. The following text has been included.

“The chosen damage curves do not include uncertainties, and they are used as recommended by the Administration at each study site. This implies that damage ranges and damage-hazard relations are different and therefore, final impact levels (from none to high) are site-specific. This assumption aimed to better communicate results to local stakeholders.”

Section 3.6:

RC12. To my understanding the probability tables of the BN are constructed by simulating a storm scenario for each combination of states and running the deterministic model chain to receive a predicted hazard value for each receptor in the study area. Due to the deterministic character of the model chain, the resulting distribution for the hazard variables does not represent probabilities, but the expected fraction of receptors with the single hazard levels or impact levels respectively.

AA. See answers to comments 9 and 10.

RC13. Since no uncertainties are considered, I see no need to apply BNs in this context.

The same calculations can be done by applying the model chain directly. A direct application of the model chain would also avoid the discretization of the variables and consequently achieve a higher accuracy.

In my point of view, the revised paper should either do without the BN approach or account for the uncertainties related to the single model components.

AA. It is true that not all potential uncertainties are considered, but we disagree with the fact that uncertainties are not considered. Thus, uncertainties due to variability inside each bin combination are included in the assessment. With respect to model-related uncertainty, it was not the aim of this application to account for the uncertainties of single model components. There is no such thing as “applying the model chain directly” since we need to integrate all results for all possible combinations in a usable way, i.e. in a format that is also suitable for coastal managers. In this sense, the use of the BN facilitate the integration of obtained results from multiple simulations when assessing scenarios. If hazards and impacts are discretized according to the vulnerability curves, the main loss of “accuracy” is due to the spatial discretization of the hazard and/or receptors exact location and size/shape. Then it could be argued that it is not very useful to report the individual hazard level of every single receptor, but that an aggregation into "fractions at different hazard levels per area" is needed to convey insight to decision makers.

The developed BNs can also be used to assess other uncertainties related to lack of knowledge. This would be the case in which the distribution of Hs is known but we have not information about associated durations. In this context, the user can leave the duration unconstrained to integrate the results from all possible durations in the output.

In addition to this, the use of the BN also allows the user to gain insight in the main drivers of hazards and impacts (BN in reverse mode or backward prediction, see results about figures 15 and 16).

With respect to this we have included the following text in the Discussion section

"*Uncertainties associated with the pathway are related to the selection of the process-oriented models used to simulate induced hazards. In the current analysis, we have not considered this source of uncertainty since the framework is applied by using previously selected models and recommended damage curves. As it was mentioned in the method section, the selected model to simulate storm-induced hazards is XBeach (Roevilnk et al. 2009), which is currently one of the most applied at the international level. Applied model setting has been selected for each case study based on local calibrations and validations for selected storm impacts. This step has to be done prior to BN development since it will control the accuracy of estimated hazards intensity and it is also a source of uncertainty. In any case, the methodology can easily deal with this source of uncertainty if simulations from multiple models or model settings are used to feed the BN.*".

Section 4:

RC14. I do not understand which storm intensity is considered here? Are the presented results the joint distribution for all possible combinations of storm characteristics? If so, what is the meaning? Is this a kind of average storm? <- I don't think so. I would rather prefer to consider specific storm scenarios in combination with their return period. E.g. what are the effects of DRR measures for a once-in-a-year oronce-in-10-years event or for an extreme event. To judge the efficiency of DRR measures, it would also be interesting to get some information about the costs of their implementation and their probability of failure.

A.A. The following paragraphs have been included to clarify these points:

At the beginning of the Results section:

"*In this section, the results of scenario testing are provided for each case study through an integrated comparison of percentages of receptors at each level of flooding and erosion risks. This is done by comparing the risk levels under current and climate change scenarios with and without measures. In any case, it has to be taken into account that this assessment does not include the statistical distribution of storm variables. We assume that there is no prior knowledge on their distributions and, as consequence, we simply describe them with a uniform distribution. This approach is adequate to explore scenarios and to assess the efficiency of protection measures in terms of impact reduction.*".

And in the Discussion section:

"*No prior knowledge of storm characteristic variables was assumed, representing them with uniform distributions. This was enough to communicate scenarios and measure efficiencies to stakeholders by integrating the BN in a multicriteria analysis such as in Barquet and Cumiskey (2017). In such multicriteria assessments, BN output is combined with information on additional elements required for decision making such as economics, endurance, ecological, stakeholders' perception, allowing for the final evaluation of alternatives. As it has been mentioned before, the next step should be to reproduce the local maritime climate to analyse this performance taking into account the relative frequency of each condition.*".

Section 5:

RC15. page 21, line 11: "a first test to check the method was presented" <- Where?I could not find any validation of the presented model. There is only a reference to a (not published) paper to validate the hazard component of the model chain.

AA. This is similar to comment RC3 and the answer to it is the same. The sentence was not referring to models validation.

RC16. page 21, line 11-15: A more detailed justification for the chosen amount of intervals and the interval boundaries, would be nice. Additionally, some information about how the computational costs scale with the number of intervals could be provided. Several uncertainties related to the study are not discussed (see comments about section 3).

AA. This is similar to comment RC4 and answer is also applicable here. To clarify this point, we have included the following paragraph in Section 5

"*With respect to the definition of sources, the BN has been built by chosen storm variables limited to those previously identified as the most important to control the magnitude of storm-induced hazards at each site. Once identified, they were discretized in equal intervals covering the whole range of so far observed values. We have used a limited number of combinations to cover the most important storm classes in terms of induced hazards and damages (Armaroli et al., 2009, 2012; Mendoza et al., 2011). Increasing the number of storms will allow to better reproduce the inherent climate variability and to characterize better this source of uncertainty in the assessment. In spite of this, used values can be considered as representative for forcing conditions in both areas and, in this sense, they will allow to use the framework to assess the efficiency of tested measures to reduce inundation and erosion risks for each given conditions"*.

We have also included a note on computational effort in section 3.6.1:

"*The used number of intervals is a compromise between accuracy and computational effort. Each combination showed in Table 1 has been simulated twice to account for potential variability inside bins. Then, all simulations are repeated for DRR scenarios affecting hazards (i.e. Winter Dune and Nourishment + Dune). Therefore, a total number of 96 model runs were required for the applied bin set-up. As a reference, using parallel simulations with 48 threads, the ratio computation time over real storm time was ~0.2, meaning that a 40 hr storm takes ~8 hours of simulation time*.".

About the uncertainties, the overall additions performed in all sections, including discussion, clarifies which uncertainties are not included in the assessment and how the BN approach is here used. Additionally, see also answers to referee #2 on comments 4,6 and 7, where we have included more discussion on uncertainty sources.

technical corrections

RC17. page 4, line 24: 2-3m?

AA17. It has been rephrased to "*The coast is about 130 km long and characterized by low-lying, predominantly dissipative sandy beaches. The coastal corridor has low elevations, mainly ranging from -2 to 3m above MSL (Regione Emilia-Romagna, 2010)*"

RC18. page 5, line 16-17: Armaroli et al (2012) is cited double

AA18. Thanks. It has been addressed.

RC19. page 11, line 19: check >0.05m or >0.5m

AA19. It has been rephrased to "*Erosion was considered present if >0.05m (vertical) and significant when >0.5m. The erosion risk categories for each receptor were set as follows: (i) Safe: no erosion in any buffer, (ii) Potential Damage: when erosion is present in the 10-m buffer and/or present but not significant in the receptor itself, and (iii) Damage: when the erosion limit of 0.5 m is exceeded within the receptor limits*"

RC20. page 14, line 31: "it also provided ..." What is "it"?

AA20. It has been rephrased to "*Alongside the generic structure, a c++ programme that automatically creates the BN (https://github.com/openearth/coastal-dss) is also provided*"

Answer to #2 referee's review

RC. Introduction

This paper presents an approach to integrated risk assessment for coastal areas with regard to storm impact on beaches (*i.e.*, flooding and erosion), considering climate change. Two case studies are presented from the Mediterranean Sea, one from the northern Spanish coast and one from the Italian coast in the northwest part of the Adriatic Sea. The methodology employed involves simulation with deterministic models for a fixed number of storm scenarios, subsequently being generalized to involve a probabilistic approach using Bayesian statistics.

RC. Overall Assessment

The paper presents an interesting and potentially useful methodology for estimating the risk associated with storm impact in coastal areas. It is in general clearly and well written; however, the paper is rather long and "wordy", presenting a lot of detailed information not really needed. On the other hand, certain aspects of the study should be discussed and explained more.

In summary, the following weaknesses of the paper should be addressed: (1) reduce the length of the paper by eliminating detailed results from the study sites; (2) expand the discussion on how coastal managers may use the results of the proposed risk assessment in their work; (3) motivate the selection of models in the approach; (4) discuss the importance of other factors influencing long-term coastal evolution not considered in the approach; (5) clarify the discussion of the methodology and concepts used; (6) comment upon the effects of antecedent morphology and chronology of forcing; and (7) explain the description of beach response to sea level rise.

I recommend that the paper is accepted after major revisions.

The general comments are given in more detail below followed by comments to specific points in the paper.

AA. Thanks for comments and suggestions on submitted manuscript. In what follows we answer to all comments/suggestions/questions raised by the reviewer.

RC. General comments

The authors are requested to address the following comments of a more general nature:

RC1. Reduce the length of the paper by eliminating detailed results from the study sites. The paper is rather long and could be shortened by cutting some of the detailed results from the two study areas. The results from these areas are interesting mainly as an illustration of what the methodology can produce; the specific values are of little interest to the readers in general. Thus, many of the figures 10-18 can be eliminated without loss of information.

AA. We agree that the manuscript is "wordy" manly due to details provided about results of case studies. Following reviewer's suggestion, we have reduced the length of the paper. Thus, we have eliminated Figures 12, 13 and 14 from the Tordera Delta results and Figure 16 from Lido degli Estensi-Spina results (and corresponding pieces of text). With this, we focus on the most relevant receptors for each case and hazard. Thus, in the Tordera case study, inundation and erosion assessments are analysed for campsites and infrastructures respectively. On the other hand, "beach concessions" is the only receptor considered for the Italian case. This does not affect to already observed future trends neither the estimated performance of DRR measures. In addition to the mentioned text cut, we have avoided to provide too much specific values and we have concentrated in characterising the general trends, and leaving the figures as elements where the reader can check obtained values. With this we are taking out 4 of the 9 figures and corresponding text from the original version of the manuscript.

In addition, the whole document was reviewed to avoid repetitions, long sentences and number of acronyms.

RC2. Expand the discussion on how coastal managers may use the results of the proposed risk assessment in their work. The discussion section is very good and informative, indicating strength and weaknesses of the methodology. However, I would like to see the authors present more of their thoughts on how managers can use the results coming out of the proposed risk assessment and advantages compared to how things are done presently. Also, are coastal managers ready to grasp this type of information, especially when it involves probabilistic concepts? In the end risk levels are presented in a qualitative manner through different categories. Would it be possible to be more quantitative?

AA. We have added the following short note in the Introduction:
"At both study sites, the tested measures were pre-selected taking into account the outcome of interviews to stakeholders (see Martinez et al., 2017) and the obtained results were used in a participatory process to select acceptable measures on the basis of a multicriteria analysis (see Barquet and Cumiskey, 2017)".

Additionally, we have added the following paragraph in Discussion:

“The presented work is part of a larger investigatory process (see Martinez et al., 2017) where stakeholders and end-users were interviewed to select possible measures for critical coastal areas (i.e. local scale). The objective of the present work was to provide rather simple information on the efficiency of measures to be used in a participatory process (see Barquet and Cumiskey, 2017) aiming at selecting acceptable measures to be applied as part of an integrated local strategy for risk reduction.”

[…]

“*We have used a limited number of combinations to cover the most important storm classes in terms of induced hazards and damages (Armaroli et al., 2009, 2012; Mendoza et al., 2011). Increasing the number of storms will allow to better reproduce the inherent climate variability and to characterize better this source of uncertainty in the assessment. In spite of this, used values can be considered as representative for forcing conditions in both areas and, in this sense, they will allow to use the framework to assess the efficiency of tested measures to reduce inundation and erosion risks for each given conditions. No prior knowledge of storm characteristic variables was assumed, representing them with uniform distributions. This was enough to communicate scenarios and measure efficiencies to stakeholders by integrating the BN in a multicriteria analysis such as in Barquet and Cumiskey (2017). In such multicriteria assessments, BN output is combined with information on additional elements required for decision making such as economics, endurance, ecological, stakeholders’ perception, allowing for the final evaluation of alternatives. As it has been mentioned before, the next step should be to reproduce the local maritime climate to analyse this performance taking into account the relative frequency of each condition.”*.

About the last question “would it be possible to be more quantitative?” The answer is yes: in the methodology section, the reader can see how relative damage is the actual output from the BN for the inundation hazard. Thus, further analysis with quantitative results could be performed (e.g. economic impact estimation derived from relative damage). However, we are presenting results as they were showed to the stakeholders, in order to easily interpret efficiencies. This is the basis of the MCA analysis explained in Barquet and Cumiskey (2017) where the addition of other information and the participation of many (multiple) stakeholders is key to finally obtain a DRR selection.

RC3. Motivate the selection of models in the approach. The basis of the methodology is deterministic simulations that are employed in a probabilistic approach through the Bayesian model. What was the reasoning when selecting the present deterministic models, which are rather detailed and time-consuming to run? Could simpler models have been employed for which many more simulations could have been made? How was the balance selected between the deterministic and probabilistic parts of the approach?

AA. In principle any model can be used but results will be as good as accurate the model will be. With this in mind, the model selection is the result of the balance between accuracy and cost. Since the model chain is not designed to provided daily forecasting (as an Early Warning System would do) computation time is not a major issue. Due to this, we have selected a process-oriented model specifically designed to simulate coastal storm-induced processes which is able to provide an integrated assessment of inundation and erosion hazards, the Xbeach model, which is one of the best available models to simulate storm-induced morphodynamics. However, the proposed framework can work with different (simpler) models provided they are able to simulate the target processes (inundation and erosion). The motivation of model selection will be stressed using what's formerly explained, in the first paragraph of section 3.3. Thus, the new first paragraph now states: "*To simulate the pathway and obtain hazards of interest, a model chain was designed and adapted for each site (Figure 4, II). Any model can be used within the model chain, and results will be as good as accurate the model. The chain must be able to reproduce all hazards to be assessed (i.e. erosion and inundation). To do this, a detailed 2D process-oriented model designed to simulate coastal storm-induced processes is used, which is able to provide integrated information on inundation and erosion, the Xbeach model (see Roelvink et al., 2009 for model details). At present it is becoming the S-O-A model on coastal systems. However, the proposed framework can work with different (simpler) models provided they are able to simulate the target processes (inundation and erosion). The Xbeach model was used in both study cases.*"

And also in the Discussion section:
"*Uncertainties associated with the pathway are related to the selection of the process-oriented models used to simulate induced hazards. In the current analysis, we have not considered this source of uncertainty since the framework is applied by using previously selected models and recommended damage curves. As it was mentioned in the method section, the selected model to simulate storm-induced hazards is Xbeach (Roevilnk et al. 2009), which is currently one of the*

most applied at the international level. Applied model setting has been selected for each case study based on local calibrations and validations for selected storm impacts. This step has to be done prior to BN development since it will control the accuracy of estimated hazards intensity and it is also a source of uncertainty. In any case, the methodology can easily deal with this source of uncertainty if simulations from multiple models or model settings are used to feed the BN."

With independence of the model to be used, it provides the deterministic response of the system. The probabilistic character is provided by the forcing (i.e. storms). The BN works as a result integration and post-processing tool. The balance between deterministic and probabilistic will depend on the information available at the study site and the way the BN is feed. We have addressed this point in answers to comments [9, 10 and 12] of referee#1. More insight on this is given in the general part of the results section (small note) and in the discussion section.

RC4. Discuss the importance of other factors influencing long-term coastal evolution not considered in the approach. The approach focuses on the impact of storms, specifically flooding and erosion. However, storms are only one of the many factors controlling beach evolution. On some coasts storms will be the primary drivers of beach change, but quite often other processes, such longshore transport gradients, sediment input from rivers, and subsidence, must be included to determine how the beach evolves over longer time periods. Typically, there is a coupling between longshore and cross-shore processes that needs to be taken into account in estimating beach evolution. Add some discussion.

AA. The reviewer is also right. However, it has to be considered that the presented framework is designed to analyse storm-induced coastal response. Thus, the presented framework is not forecasting the coastal morphology at any given time (where it should be necessary to couple all processes) but it predicts the expected storm-induced changes for a given coastal configuration. In that sense, a long/medium term model could be used to forecast a future coastal morphology under a given climate scenario and then, use it as initial configuration to forecast storm-induced changes. This was done here with long term coastal response to SLR, where coastal morphology was modified to simulate its effect in Tordera Delta. This could be done externally with any additional processes acting on a system such as the existence of a gradient in the longshore transport which will induce a background erosion. We have included the following paragraph (in Discussion, before 5.1):

“*Another point to be considered is that this assessment framework has just been designed to analyse the storm-induced coastal response. This implies that used models does not forecast the coastal morphology at a given time (where it should be necessary to couple all governing processes) but predict the expected storm-induced changes for a given coastal configuration. As storm-induced hazards depend on existing morphology at the time of the impact (e.g. Cohn and Ruggiero, 2016), the initial morphology used in the model is also a source of uncertainty. To overcome this, a long/medium term morphological model (Hanson et al. 2003;Lesser et al. 2004) could be used to forecast the future coastal morphology under a given climate scenario at a given time and then, to use it as the initial configuration to assess storm-induced changes. This has been illustrated here by considering the change in estimated risks due to sea level rise in Tordera Delta. This approach can also be applied to assess the effects of consecutive storm impacts (Coco et al. 2014) by using estimated post-storm bed levels as pre-storm morphology for given storm combinations. Once this extra information is included in the BN, the uncertainty associated to future shoreline configurations on assessed risks can be analysed.*”

RC5. Clarify the discussion of the methodology and concepts used. The paper is rather clear on the methodology, but sometimes it is a bit difficult to follow and the sentences become long and affected by jargon. I also have a bit of a problem with how the source-pathway-receptor model is translated to the storm case. The storm is the source and erosion/flooding is the pathway; this seems a bit different (and less logical) from the experience I have in looking at pollution transport. Anyway, may be the writing about and motivation of the schematization could be made a bit clearer. Also, although abbreviations make things a bit easier, if there are too many it is difficult for the reader to remember all of them.

AA. See PATHWAY concept rephrased to: “*These storms propagate through the pathway, causing erosion at the coast and inundation on the hinterland. Both hazards are the main focus of the analysis*” in section 3.1.

In addition, as we also got the same comment from referee#1 regarding abbreviations. We have reduced abbreviations to a minimum, and we use full wording for most concepts.

RC6. Comment upon the effects of antecedent morphology and chronology of forcing. Morphological response is very much a function of the antecedent conditions as well as the chronology of the forcing, especially when it comes to storms. For example, if a large storm is followed by a similar large storm the second one will cause much less erosion. Thus, looking a storm impact as individual events will cause some limitations in terms of the impact assessment. Please add some discussion on this.

AA. The authors agree with the statement about the chronology of forcing and consecutive storms. This is another process controlling initial coastal configuration (morphology) where the storms will impact. See answer to comment 4.

RC7. Explain the description of beach response to sea level rise. The response of a profile to sea level rise requires some assumption about the evolution of different morphological features, for example the dune (e.g., will the dune grow to its pre-SLR shape?). Some additional discussion on the assumptions made in this respect would be interesting.

AA. The current state of the description of the application of the Brunn rule is "*This was accomplished assuming an equilibrium coastal profile response following the Bruun rule (Bruun, 1962), resulting in landward and upward displacement of the beach profile*" (P12 L11). We specify here that dunes preserve the pre-SLR shape when there's enough accommodation space, and the shape was cut where there wasn't enough space (right after the sentence). Then in the discussion we have added a paragraph about uncertainty associated to this choice. The included text is: "*When considering SLR-induced effects on time evolution of storm-induced risks, we have to take also into account existing uncertainties. Thus, the first uncertainty is related to the magnitude of the change itself. Here we have used the RCP8.5 SLR scenario but other scenarios could be possible (Church et al. 2013). The other source of uncertainty is controlled by the way in which this forcing is translated to the system. In this work we have assumed the Bruun rule to be valid and it was used to generate a morphological accommodation of the Tordera Delta site to SLR. Since there is no consensus on the best model to simulate this effect, other existing models and approaches (see e.g. Le Cozannet et al. 2014) could be tested and integrated in the BN to include this uncertainty. In any case, the effect of the uncertainty on the SLR projections may be larger than their associated morphological response.*".

RC. Specific comments

In the following specific comments are given to the paper (L = Line number; P = page number).

P4, L14

“wave-induced run-up” Includes wave setup? Any consideration of duration with regard to having water at a certain location?

AA. It is a general statement comparing the contribution of run-up (including set-up and swash, we will add this in brackets) to the total water level (astronomical tide + residual (surge) + run-up). We are not considering any time duration here, since tide and surge are never the direct cause of flooding in the NW Mediterranean, being this the wave-by-wave overtopping. Thus, the surge only plays the role of “lowering the freeboard of the beach some centimetres (tens in the worst case)”, and was considered not to be significant enough compared to waves’ contribution to include it as a variable in the BN (i.e. having multiple classes of sea level for the current situation).

P5, L19

“thresholds” How sensitive are the methods to the selected thresholds? Was this selection based on impact or purely on the forcing properties (offshore wave conditions)? The probability of extreme events with regard to the former and the latter are typically different.

AA. The authors are well aware of the different statistical results obtained by the event approach (selection based on storm characteristics) or the response approach (statistics based on impacts/hazards) and have studied its effect of inundation hazard statistical identification. The presented method is not sensitive to the thresholds to identify events the way it is applied in the sense that we are not assigning probabilities or return periods to a given inundation. We are integrating results from multiple scenarios by equally representing them (same storm simulations for each source characteristic state of variables). In this section we are only explaining how storm events are usually identified in the study sites, for the reader to know what a storm means in the Adriatic or in the NW Mediterranean.

In the text the reader is currently pointed to the corresponding references where these thresholds were derived, which are based on impact.

P8, L18

“XBeach model” How good was the calibration/validation?

AA. Currently we are providing only the reference to the study at the Tordera Delta were the validation is explained in detail. We have included a note at each study site paragraph describing briefly how good the validation was, in terms of Brier Skill Score, so the reader can have some additional info in the present manuscript and not only the references. See in the text: *“The model chain was validated through the St Esteve event in 2008, obtaining a Brier Skill Score of 0,682* *for the morphological response of the emerged part of the beach (Sanuy and Jiménez, n.d.). Simulation results can be considered excellent for scores over 0.6 (Sutherland et al., 2004)"*

P9, L14

"intersecting" Meaning in this context?

AA. Polygon intersection, between receptors 2D layout and the Xbeach grid. This way we identify which grid nodes affect each receptor. We have clarified

P11, L16

"footprint" What is this?

AA. Is the receptor polygon layout in 2D. We now use "receptor limits in the ground".

P12, L14

"a directional change" But the wind did not change, right (L3)? What is causing this.

AA. The study reporting change in wave direction (Casas-Prat and Sierra, 2012) predicts the change in direction by applying statistics to the current past 60-year evolution of wave records, and obtaining the prediction of the future wave mean climates. Therefore, there is no information/evidence in that study linking that change to any specific forcing (wind, wave current interaction…). It is a scenario we wanted to explore as a "what if" future situation. In addition, we have changed the text from "*Other factors such as changes in storminess, wind, or waves were not expected to change significantly in the NW Mediterranean*" to "*Other factors such as changes in storminess, wind speeds, or wave high were not expected to change significantly in the NW Mediterranean*"

P13, L14

"winter dune" What is this?

AA. It's the name given to an artificial dune which is built every winter to protect beach concessions in Emiglia-Romagna (Italy). It is explained in the consecutive paragraph and we will cross-reference it

P18, L18

From here on some of the figure numbers are wrong. Please check.

AA. This will be addressed, since some figures have been supressed and the whole text on the results section reviewed and reduced.

P18

Some of the DRR measures taken seem to increase the risk. What is the explanation/logic behind this? Does it mean that the characterization of impact is not proper?

AA. In the Tordera Delta, this is the case when the DRR affects the hydrodynamics at the nearshore and or swash zone, and while protecting locally some receptors, but the erosion is increased down coast and other receptors get more exposed than before. Overall it can be observed how this increase isn't significant in any case. Nevertheless, the figure containing this effect will be supressed due to comment 1 and thus, it will not induce confusion to the reader or require further explanation by the authors.

In Lido degli Estensi and Spina, this is the case when the Winter Dune is close to the receptors it must protect, and it fails to prevent overwash. The measure increases water speed and can enhance scouring in such specific cases. We have added a small note about this phenomenon in the Results section of the Italian case: "*Simulation results show that when the dune is present with concessions close at its rear, and the storm overcomes the measure, water arrives with enough velocity to produce scouring at the first concessions*."

Linking source with consequences of coastal storm impacts for climate change and risk reduction scenarios for Mediterranean sandy beaches

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Abstract. Integrated risk assessment approaches to support coastal managers' decisions when designing plans are increasingly becoming an urgent need. To enable efficient coastal management, possible present and future scenarios must be included, disaster risk reduction ~~(DRR)~~ measures integrated, and multiple hazards dealt with. In this work, the Bayesian Network approach to coastal risk assessment was applied and tested at two Mediterranean sandy coasts (Tordera Delta in Spain and Lido degli Estensi-Spina in Italy). Process-oriented models are used to predict hazards at the receptor scale which are converted into impacts through vulnerability relations. In each site, a total of 48 storms have been simulated under different scenarios and obtained results are integrated by using a Bayesian Network to link forcing characteristics with expected impacts through conditional probabilities~~Process-oriented models are used to predict hazards at the receptor scale based on a large number of storm characteristics. Hazards are converted into impacts through vulnerability relations. A Bayesian Network integrates all results to link forcing characteristics with expected impacts through conditional probabilities~~. Consultations with local stakeholders and experts have shown that the tool is valuable for communicating risks and the effects of risk reduction strategies. The tool can therefore be valuable support for coastal decision making~~The tool has been proven successful in reproducing current coastal responses at both sites. It has also shown great utility for scenario comparisons, and is able to output significant impact change trends, despite the inherent uncertainties of the approach. This work highlights the advantages of using such a tool for present and future coastal risk assessment and planning~~.

Keywords. Disaster Risk Reduction, Source-Pathway-Receptor-Consequences, Bayesian Network, Catalunya, Emilia-Romagna, Coastal Risk Management, Erosion, Flooding.

1 Introduction

Increasing coastal risk due to the intensification of hazard and exposure magnitudes (IPCC, 2012; IPCC, 2013), is driving the needs of coastal managers towards more innovative approaches for coastal risk assessment and management.

~~Highlighting these needs at~~At the international and ~~European~~ European levels these needs are highlighted by ~~is~~ the impact of recent extreme events such as Hurricane Katrina in Louisiana in 2005 (Beven II et al., 2008), storm Xynthia in France in 2010 (Bertin et al., 2012; Kolen et al., 2013), Hurricane Sandy in New York in 2012 (Kunz et al., 2013; Van Verseveld et al., 2015), and the Southern North Sea storm in 2013 (Spencer et al., 2015). Similarly, in the Mediterranean, several extreme events have impacted coastal communities at the local and regional levels such as storm Klaus in 2009, as described in Bertotti et al. (2012) and cyclogenesis mechanisms in the NW Mediterranean described in Trigo et al. (2002). In this context, the coasts of Catalunya (Spain) and Emilia-Romagna (Italy) also recently experienced coastal storm impacts that caused socio-economic losses (Jiménez et al. 2012; Perini et al., 2015; Harley et al., 2016; Trembanis et al., n.d.).

Therefore, coastal managers must properly deal with coastal risk when designing plans. This is recognised in several initiatives such as the protocol of Integrated Coastal Zone Management (ICZM) for the Mediterranean, which includes a chapter on natural hazards and advises signed parties to implement vulnerability and risk assessments. In addition, the EU Floods directive is another example dealing specifically with floods. Therefore, the need for integrated decision support systems ~~(DSS)~~ based on modern ~~models and~~ approaches for coastal risk assessment ~~and management~~ is increasing. ~~Indeed, c~~Coping with storm-induced risks in coastal areas involves testing multiple ~~disaster~~ risk reduction ~~(DRR) alternatives~~measures against multiple forcing conditions in current and future scenarios considering climate change.

The literature provides different approaches with which to implement these assessments. It is becoming increasingly important to consider multi-hazard approaches when assessing risk at all levels (i.e. from the regional to local scales). Therefore, the scientific community provides integrated and interdisciplinary approaches (e.g. Ciavola et al., 2011a; Ciavola et al., 2011b; Penning-Rowsell et al., 2014; Vojinovic et al., 2014; Oumeraci et al., 2015; Van Dongeren et al., ~~n.d.~~2017). Up-to-date methodologies can be used in coastal risk assessments at different scales ranging from regional ~~approaches~~ (up to hundreds of km) to local ~~detailed~~ assessments (up to 10 km). Regional methodologies aim to locate coastal sectors more ~~prone~~ sensitive to impacts, the so-called hotspots. Local approaches aim to achieve the highest possible level of accuracy for risk evaluation and to support decision making for previously identified hotspots. Notably, coastal risk assessments must include physical concepts to characterise physical phenomena (i.e. the source of the hazard) and socio-economic concepts to describe the impact of the physical phenomena on human assets (i.e. the consequences). A ~~suitable~~ conceptual flexible framework that can capture all aspects of coastal risk assessment is the Source-Pathway-Receptor-Consequence (SPRC) model (e.g. Narayan et al. 2014, Zanuttigh et al. 2014 and Oumeraci et al., 2015).

When addressing the problem at the local scale, it is necessary to accurately predict the impact and reproduce in detail coastal hazards~~ and responses~~. The analysis of physical impacts is regularly implemented ~~in a deterministic way,~~ with process-based numerical models ~~playing a central role and~~ providing detailed information for areas prone to multiple hazards (e.g. Roelvink et al., 2009; McCall et al., 2010; Harley et al., 2011; Roelvink and Reniers, 2012). However, ~~this must be used with~~ multiple forcing conditions acting at the site and under different scenarios must be evaluated~~. This implies a probabilistic approach to deal with the inherent uncertainty of the problem. To obtain the best benefits from deterministic and probabilistic approaches, the integration of process-oriented tools can be combined with a probabilistic-based analysis of~~

~~their results~~. Bayesian Networks (BNs) have demonstrated their versatility and utility in efficiently combining multiple variables to predict system behaviour for multiple hypotheses (e.g. Plant et al. 2016). Using a BN approach, ~~multiple~~ many multi-hazard results from process–oriented models can be integrated for joint assessment, ~~as well as for~~combining different scenarios and alternatives (e.g. Gutierrez et al., 2011; Poelhekke et al., 2016), enabling the integration of socio-economic concepts (e.g. Van Verseveld et al., 2015).

Jäger et al. (2017) proposed the conceptual BN framework used in this work, which is based on the integration of the SPRC and was developed in the RISC-KIT EU FP7 project (Van Dongeren et al., ~~n.d~~2017~~.~~). Plomaritis et al. (2017) applied the framework to test its potential as an early warning system ~~(EWS)~~ and the response of ~~DRRs~~ risk reduction measures in Ria Formosa (Portugal). In this paper, the authors describe the application of the framework adapted to select and compare strategic alternatives to reduce coastal risk in current and projected future climate scenarios. The application in this paper was conducted at two sedimentary coasts in the Mediterranean environment, namely the Tordera Delta for the Catalan coast (Spain) and the Lido degli Estensi-Spina for the Emilia-Romagna coast (Italy). At both study sites, the tested measures were pre-selected taking into account the outcome of interviews to stakeholders (see Martinez et al., 2017) and obtained results were used in a participatory process to select acceptable measures on the basis of a multicriteria analysis (see Barquet and Cumiskey, 2017).

Figure 1: Regional and local contexts: A1) the central-northern Catalan coast; B1) Emilia-Romagna coast; A2) local hotspot~~s~~ of Tordera Delta; B2) local hotspots of Lido degli Estensi-Spina (2b). The main locations (red dots), wave buoys (red triangles), tide gauge (red diamond), and the ~~CSS~~ case study sites (red squares). The domains of the large-scale and local models (dashed red lines) are highlighted for each box.

2. Regional contexts and case studies

The two presented case study sites ~~(CSS)~~ are representative of many other coastal areas in the Mediterranean consisting of sandy beaches where local economic activities are based on the tourist sector. These areas are characterised by urbanisation and infrastructural growth close to the shoreline (limiting natural beach accommodation processes) and economic activities ~~directly~~ located on the beach and immediate first part of the hinterland (e.g. concessions, campsites, restaurants). The coast keeps offering its recreational function, but ~~lacks~~ loses ~~part or all of~~ its protective function against storms. ~~Thus, depending on the morphological conditions of~~In addition, the hinterland ~~and~~ is exposed~~ure~~ to ~~incoming~~ storms-induced hazards~~,~~. ~~these coastal areas are prone to becoming sectors sensitive to the impact of extreme events.~~

2.1 Tordera Delta, Catalunya (Spain)

The Catalan coast is located in the ~~NE Spanish~~NW Mediterranean Sea (Figure 1, A1). It consists of a coastline 600 km long with about 280 km of beaches. Coastal damage has increased during the last decades ~~along regional coasts~~ as a result of the increasing exposure along the coastal zone and progressive narrowing of existing beaches (Jiménez et al., 2012) through dominant erosive behaviour due to net littoral drift (Jiménez et al., 2011). Locations experiencing storm-induced problems are present along the entire coastline, and are especially concentrated in areas experiencing the largest decadal-scale shoreline erosion rates. Among these areas, the Tordera delta, located about 50 km north of Barcelona, provides a good example (Jiménez et al., 2017b)(Figure 2).

The deltaic coast is composed of a coarse sandy coastline extending about 5 km from s'Abanell beach at the northern end and Malgrat de Mar beach in the south (see Figure 2). This zone is highly dynamic, and is currently in retreat as a result of the net longshore sediment transport directed southwest and the decrease in Tordera river sediment supplies. Consequently, the beaches surrounding the river mouth, which were traditionally stable or accreting, are being significantly eroded (Jiménez et al., 2011; Sardá et al., 2013). As a result of the progressive narrowing of the beach in the area, the frequency of inundation episodes and damage to existing infrastructure (beach promenade, campsite installations, desalination plant infrastructure, roads) has significantly increased since the beginning of the 90s (Jiménez et al., 2011; Sardá et al., 2013) (Figure 2).

Subsequently, existing campsites in the most affected area have abandoned the areas closer to the shoreline, as in many cases, these areas are fully eroded or directly exposed to wave action. In other cases, owners have tried to implement local protection measures that in many cases have enhanced existing erosion (Jiménez et al., 2017b).

Coastal storms in the Catalan Sea can be defined as events during which the significant wave height (Hs) exceeds a threshold of 2 m for a minimum duration of 6 hours (Mendoza et al., 2011). Despite this, not all storms can be considered as hazardous events in terms of induced inundation and/or erosion. Mendoza et al. (2011) developed a five-category storm classification for typical conditions in the Catalan Sea based on their power content. The classification seems to well represent the behaviour of storm events in the Mediterranean, and was successfully employed in the Northern Adriatic (Armaroli et al., 2012). Furthermore, Mendoza et al. (2011) estimated the expected order of magnitude of induced coastal hazards (erosion and inundation) for each class and beach characteristics along the Catalan coast. According to their results, storms from category III (Hs = 3.5 m, duration around 50 hours) to V (Hs = 6 m, duration longer than 100 h) are most likely to cause significant damage along the Catalan coast. One important aspect to consider is that wave-induced run-up (setup + swash) is the largest contribution to ~~the total water level (TWL)~~overwash at the ~~shoreline~~ beach during storm events, because the magnitude of surges along the Catalan coast is relatively low (Mendoza and Jiménez, 2008).

Figure 2: Impacts on the Tordera Delta. Destruction of a road at Malgrat (A); overwash at campsites north of the river mouth (B); destruction of the promenade north of the river mouth (C); beach erosion, and damage to utilities and buildings at Malgrat (D and E).

2.2 Lido degli Estensi-Spina, Emilia-Romagna (Italy)

The Emilia-Romagna (Italy) coast is located in the northern part of the Adriatic Sea (Figure 1, B1). The coast is about 130 km long and characterized by low-lying, predominantly dissipative sandy beaches. The coastal corridor has low elevations, mainly ranging from -2 to 3m above MSL (Regione Emilia-Romagna, 2010)~~The coastal corridor has low elevations (-2÷3m; Regione Emilia-Romagna, 2010)~~. The area alternates between highly urbanised touristic zones and natural areas with dunes, which are often threatened by flooding and erosion (Regione Emilia-Romagna, 2010). The impact of coastal erosion was emphasised by subsidence due to water and gas extraction over the last century, especially in the Ravenna area (Taramelli et al., 2015), a decrease in riverine sediment transport, because of the strong human influence on rivers and their basins (Preciso et al., 2012), and the reforestation of the Apennines (Billi and Rinaldi, 1997). Touristic activities (accommodation, restoration, sun-and-bathe) can be considered main drivers of the coastal economy. Beach concessions, which provide sun-and-bath and restoration services, have grown exponentially in number since the second half of the last century, with negative consequences on natural areas, as in Ravenna Province (Sytnik and Stecchi, 2014). To protect the coast and its assets from the impacts of flooding and erosion, regional managers have constructed hard defences (e.g. emerged and submerged breakwaters, groins, rubble mounds; Regione Emilia-Romagna, 2010) along the entire regional coast (over 60% of the coast is protected), and regularly implement restorative nourishment plans.

During the last decades, several EU projects such as Theseus (www.theseusproject.eu) and MICORE (www.micore.eu) provided a good understanding of hydro-morphodynamics and risks to the coast. These projects and works published in the international literature such as Ciavola et al. (2007), Armaroli et al. (2009, 2012), and Perini et al. (2016) were the product of strong collaboration between scientists and regional managers (Servizio Geologico Sismico e dei Suoli, SGSS). This led to the compilation and implementation of a storm database (Perini et al., 2011) and a regional EWS (Harley et al., 2016). The RISC-KIT project (www.risckit.eu) provided additional knowledge on this coastal area. The areas most exposed to coastal risk are well known, as can be seen in the works of Perini et al. (2016) and Armaroli and Duo (2017).

For a more local perspective, the Lido degli Estensi-Spina coastline (Comacchio municipality, Ferrara province, Italy) area represents a highly touristic stretch of coast with concessions directly facing the sea (Figure 1, B2). The littoral drift is northward as confirmed by the width of the sandy beaches, which increases from 20 to 50 m in the southern part of Lido di Spina to 200 to 300 m in the northern part of Lido degli Estensi. Here the sediment is trapped by the groin of the mouth of a navigation canal (Porto Canale). The beach is not protected, and regional managers implement regular nourishment in the southern part of the area (Nordstrom et al., 2015). At the back of the concessions, the villages accommodate restaurants and hotels for tourists, along with residential buildings (mainly holiday houses). In a recent study, Bertoni et al. (2015) analysed aerial photographs of the evolution of the case study area, focusing on the stretch of coast between Porto Garibaldi and the Reno river mouth. The area was impacted by the event in February 2015 (see Figure 3) with limited, but not negligible, consequences for several concessions (Perini et al., 2015; Trembanis et al., n.d.).

The hydrodynamics of the regional domain are well described in terms of storm waves and surges (IDROSER, 1996; Ciavola et al., 2007~~; Masina and Ciavola, 2011~~). ~~These are as follows: the~~The area is micro-tidal (neap tidal range: 0.3–0.4 m; spring tidal range: 0.8–0.9 m); the surge component plays an important role (1-in-2 years storm surge: 0.61 m) and is mainly generated from the SE (Scirocco) winds (according to the orientation of the Adriatic Sea). Furthermore, the wave climate is low energy (mean Hs –0.4 m; 60% of waves are below 1 m). However, extreme events can be energetic, such as the storm of September 2004 (Hs,max=5.65m, estimated by Ciavola et al,. 2007) or the one of 5-6 February 2015 (Hs,max=4.66, measured at the Cesenatico buoy shown Figure 1, B1; Perini et al., 2015; Trembanis et al., n.d.).

The combination of high waves and storm surges, whose combined probability of occurrence in the area was assessed by Masina et al. (2015), can have strong impacts at the regional level, as demonstrated by Armaroli et al. (2009), Armaroli et al. (2012),) and Harley and Ciavola (2013), and Armaroli et al. (2012). Notably, based on historical data (Perini et al., 2011), Armaroli et al. (2012) provided a set of critical storm thresholds for natural and urbanised beaches to characterise potentially impacting storms. The thresholds included a combination of offshore Hs and TWL: 1) Hs ≥ 2 m and TWL (surge + tide) ≥ 0.7 m for urbanised zones; 2) Hs≥3.3 and TWL (surge + tide) ≥0.8 m for natural areas with dunes.

For a more local perspective, the Lido degli Estensi-Spina coastline (Comacchio municipality, Ferrara province, Italy) area represents a highly touristic stretch of coast with concessions directly facing the sea (Figure 1, B2). The littoral drift is northward as confirmed by the width of the sandy beaches, which increases from 20 to 50 m in the southern part of Lido di Spina to 200 to 300 m in the northern part of Lido degli Estensi. Here the sediment is trapped by the groin of the mouth of a navigation canal (Porto Canale).The beach is not protected, and regional managers implement regular nourishment in the southern part of the area (Nordstrom et al., 2015). At the back of the concessions, the villages accommodate restaurants and hotels for tourists, along with residential buildings (mainly holiday houses). South of the case study site is a natural area with dunes, which while strongly impacted by erosion, is not considered in this study. In a recent study, Bertoni et al. (2015) analysed aerial photographs of the evolution of the case study area, focusing on the stretch of coast between Porto Garibaldi and the Reno river mouth. The area was impacted by the event in February 2015 (see Figure 3) with limited, but not negligible, consequences for several concessions (Perini et al., 2015; Trembanis et al., n.d.).

Figure 3: Impacts of the event in February 2015 on the Lido degli Estensi-Spina case study area. Impacts of erosion and flooding on concessions at Lido di Spina south (A, B) and Lido degli Estensi (C); sandy scarp due to the erosion of the dune in the south of Lido di Spina (D); eroded Winter Dune in Porto Garibaldi (E); damages to the Porto Canale front at the Lido degli Estensi (F).

3. Methodology

3.1 General approach: from source to consequences

The analysis framework employed in this study follows Jäger et al. (2017) and is based on the use of the SPRCSPRC (source-path-receptor-consequence) model (FLOODsite, 2009; Oumeraci et al., 2015), as shown in Figure 4. This model is mostly widely used in coastal risk management (e.g. Narayan et al., 2014) and permits a clear representation of all risk components and their links from source to consequence.

The Ssource (S) includes the forces determining coastal response to the impact of extreme events, which in this case are essentially a set of storms representative of the storm climates of the study sites over the entire intensity range (from moderate to extreme storms). These sources storms propagate through the pathway, causing erosion at the coast and inundation on the hinterland. Both hazards are the mainto the coast and lead to different hazard pathways (P) such as erosion and inundation, the focus of the analysis. The pathways are is solved through a process-oriented model chain to propagate storms and quantify induced processes. ~~They~~ These are assessed for the entire coastal domain where receptors ~~(R)~~ are located, characterised ~~according to~~by their location ~~on the coastal plain~~ and typology, which define their exposure~~,~~ and vulnerability to each hazard~~ type~~. Finally, consequences~~ (C)~~ are evaluated by combining the vulnerability and exposure of each receptor with the magnitude of the hazards.

Since the main objective of the analysis is to test ~~DRR~~ risk reduction strategies to help decision makers in future planning, the framework is applied under current conditions (~~hereafter current scenario,~~ CUS) ~~to~~ which define the baseline scenario and climate change conditions (~~hereafter climate change scenarios,~~ CCS) to define a plausible future scenario. Finally, the analysis is repeated considering different ~~DRR~~ risk reduction measures.

The ~~general~~ approach uses ~~the ability of~~ a Bayesian Network (~~-~~BN) to reproduce the steps of the SPRC model ~~assess~~ through dependency relations between variables~~ to reproduce the steps of the SPRC model~~. This conditions the application of the steps of the SPRC model, as explained in the following sections. At the same time, we use ~~its~~ the BN data assimilation capabilities to integrate large amounts of data, i.e. results from multiple sources at multiple receptors. ~~As such, the~~ The BN ~~can consider all~~integrates dependency relations between ~~the analysed variables~~source-hazard-consequences, at the receptor scale, ~~enabling the assessment of multi-hazards and the consequences on receptors~~ for all tested incoming conditions, scenarios, and ~~DRR~~ risk reduction alternatives in a ~~condensed, graphic, probabilistic, and~~ single tool.

Figure 4: General methodology. (I) The SPRC conceptual framework is implemented through (II) a model chain, which consists of a propagation module of the source (S) and a process-oriented module for the coastal area reproducing the pathway (P). Then, (III) the consequences (C) are calculated based on the computed hazards (H) at the receptor (R) scale by using vulnerability relations (i.e. hazard-consequences functions). In the last step (IV), all variables including source boundary conditions (BC) are fitted in a BN, adding impacts after the implementation of measures (M).

3.2 Source: identification and design

~~Since the objective of this work was to test DRR measures for risks induced by coastal storms, these are the source considered.~~ To properly characterise storms, all relevant variables controlling the magnitude of induced hazards (erosion and inundation) must be considered, in other words, Hs, wave period (Tp), wave direction, storm duration, and water level. In this approach, storm characteristics are defined in terms of a set of representative storms or storm scenarios that cover the typical conditions at each study site. This information is obtained from existing wave time series or bulk data of the events (recorded or modelled), usually in deep waters, propagated towards the coast to characterise storm conditions at the nearshore of the study areas. Probable combinations that cannot be covered using existing records are represented by synthetic designed storms (e.g. Poelhekke et al., 2016; Plomaritis et al., 2017; Jäger et al., 2017)~~. Storm scenarios are defined as a combination of the involved variables within the BN. To this end, each selected variable was categorised in discrete bins covering its probable range as a function of the climatic conditions of the study site. Then, recorded storms belonging to each bin class were selected for use in the analysis~~. The storm events were selected based on the information available for each study site through the RISC-KIT WEB-GIS impact-oriented database (Ciavola et al., 2017; http://risckit.cloudapp.net/risckit/#/), which provided ~~synthetic information on the physical parameters (measured or assessed~~

at the regional level)storm characteristics and socio-economic impacts of the events. In addition, time series of waves (either bulk Hs, Tp and mean direction or spectrum) and water levels during each storm event -were used to characterise all events for whichwhen this information was available.

For the Tordera Delta case, the selected variables to define storm scenarios were Hs at the peak of the storm, total storm duration, and incoming storm direction. Tp does not significantly vary during storms in the study area (see Mendoza et al., 2011) and was not included to reduce the number of variable combinationsas a characteristic variable. The Due to the coastline configuration and morphology, the area is sensitive to storm incoming direction (Sanuy and Jiménez, n.d.). Thus, wave climate characteristics necessitated considering the main wave directions in terms of dominant (E) and secondary (S) directionsstorms needed to be considered separatelly. Finally, TWL (tide + surge)the position of the mean sea level (MSL) during the event was included to reproduce hypothetical future projections of sea level rise (SLR) of MSL due to climate change. The selected bins for each variable can be seen in Table 1. These lead to 12 combinations defining the source under current MSL and 12 under future MSL (given by a SLR scenario). Each combination of states is simulated twice by means of slightly different storms to account for potential variability within variable ranges, leading to a total of 24 storms under the current MSL and 24 under SLRThe selected discrete bins are shown in Table 1. These lead to 12 combinations (24 simulated storms) defining the source that must be tested in the current MSL and another 12 (24 simulated storms) in the future MSL scenario. . Of the 24 source storms in the current situation, 16 correspond to historic (recorded) events including the two largest, which occurred in November 2001 and December 2008. These were classified as extreme storms (category V) according to the Mendoza et al. (2011) classification. To include the full range of cases, the remaining eight storms were completed by using combinations of Hs-duration-direction not previously recorded. These events were modelled assuming they follow a triangular-shaped evolution with the peak intensity at the half of their duration (see e.g. McCall et al. 2010; Poelhekke et al., 2016)To include a full range of combinations, the remaining eight storms were completed using synthetic triangular events that correspond to combinations of Hs-duration-direction not previously recorded. Data used to reproduce the historic events include the time series of hindcast wind fields and 2D wave spectra time series in deep waters for the NW Mediterranean (Guedes-Soares et al., 2002; Ratsimandresy et al., 2008). Wave conditions must propagate towards the coast to properly define storm events at the study site. At the Catalan coast, the storm surge contribution to the sea surface level is one magnitude lower than the wave-induced component, and the two variables are uncorrelated (Mendoza and Jiménez, 2008).. All historical events with recorded associated water levels were simulated with the real storm surge, while the synthetic storms were simulated with a storm surge of a 0.25 m constant throughout the event, as representative of the site according to the same authors. (Mendoza and Jiménez, 2008).

Table 1: Source characterization. Variable discretization applied at the study sites.Table 1: Source characterization. Variable discretization applied at the study sites.

Previous works in the area of the Lido degli Estensi-Spina case study have identified the dominant role of wave height and total water level in controlling the magnitude of storm-induced erosion and inundation (Armaroli et al 2009, 2012). Due to this, variables used to characterize the source were the maximum Hs and maximum TWL (surge+tide) during each storm event. Thus, wave period and the direction of the storms was not considered as a source characteristic variable to be discretized. Each storm was simulated for current and climate change (SLR) scenarios. Finally, and similarly to the Tordera case study, each Hs-TWL combination was simulated twice to account for potential variability. The used range for each variable is shown in Table 1.For the Lido degli Estensi-Spina case study, the source variables, identified as drivers of the impacts of flooding and erosion, were the maximum Hs and maximum TWL of the storm event. In addition, the relative sea level rise (RSLR) was considered as a Boolean variable to represent the CCS. The direction of the storms was not considered as a source characteristic variable. The ranges of the variables were classified into bins, as shown in Table 1. Seven historically based events were selected from the RISC-KIT Database, and to cover all possible combinations, 5 additional synthetic events were considered for a total of 12 events in the CUS. Notably, for several historic events, neither reliable nor continuous time series for waves and water levels were available from local measuring stations. To ensure consistency, both historical and synthetic events source events were represented based on the following methodology. Starting with the list of bulk synthetic information for each event (maximum Hs, Tp, main direction of the storm, maximum TWL or duration when available), triangular symmetric storm distributionsstorms following triangular-shaped evolution (e.g. Carley and Cox, 2003; Corbella and Stretch, 2012) for Hs, Tp, and surge were created for both historical and synthetic events. The peak of the waves was assumed to occur at the same time as the maximum surge (calculated as the difference between the TWL and maximum astronomical predicted tide). When bulk parameters were missing, the following 'worst case' assumptions were introduced: Tp at peak of 10 s, wave direction of 90º, and duration based on similarity with other storms.

3.3 Pathways: modelling multi-hazard impacts

To reproduce simulate the pathway from source (storm) to impact (hazards)and obtain hazards of interest, a model chain was designed and adapted for each site (Figure 4, II). Any model can be used within the model chain, and results will be as good as accurate the model. The chain must be able to reproduce all hazards to be assessed (i.e. erosion and inundation). To do this, a detailed 2D process-oriented model designed to simulate coastal storm-induced processes is used, which is able to provide integrated information on inundation and erosion, the XBeach model (see Roelvink et al., 2009 for model details). At present it is becoming the S-O-A model on coastal systems. However, the proposed framework can work with different (simpler) models provided they are able to simulate the target processes (inundation and erosion)simulating inundation and erosion in an integrated way was employed (the obtained inundation includes the morphodynamic feedback associated with coastal erosion during the storm). The XBeach model was used for this purpose in both study cases (see Roelvink et al., 2009 for model details).

The model chain for the Tordera Delta study case consists of two blocks, one 'external' and one 'internal'. The external module comprises three models (HAMSOM, HIRLAM, and WAM models) that supply the forcing conditions (time series of water levels, wind fields, and waves) and are run by Puertos del Estado (Spanish Ministry of Public Works). The output of these models is taken directly as an input for the internal module, which comprises the SWAN (Booij et al., 1996) and XBeach (Roelvink et al., 2009) models. SWAN was used to propagate wave conditions provided by the external models (regional scale)from deepwaters to the offshore boundary of the XBeach model (20 m depth), while XBeach was employed to assess the extension and magnitude of inundation and erosion hazards at the study site (local scale). The model chain was validated through the St Esteve event in 2008, obtaining a Brier Skill Score of 0,682 for the morphological response of the emerged part of the beach (Sanuy and Jiménez, n.d.). Simulation results can be considered excellent for scores over 0.6 (Sutherland et al., 2004)

The model chain for the Lido degli Estensi-Spina case study only included the XBeach model. This simple approach was possible based on the assumption that the information derived from the RISC-KIT Database can be considered representative of the storm in the regional domain, as collected from different sources (e.g. offshore buoys, harbours' tide gauges, newspapers, etc.) along the Emilia-Romagna coast (Perini et al., 2011; Ciavola et al., 2017). The model was qualitatively validated with the February 2015 event (Perini et al., 2015; Trembanis et al., n.d.).

3.4 Receptors and consequences

The methodology applied in this work individually identified receptors located at the study sites (Figure 4, III) (Jäger et al., 2017). First, receptors with homogeneous vulnerability characteristics were defined and separately considered. Then, for each group of receptors, polygons were drawn using a GIS-based tool to account for their exact location and size. Finally, the polygons were intersected with the cells of the 2D detailed model grid (XBeach) to assign to each receptor the nodes of the model that will affect them.

For the inundation hazard, the value of the maximum water depth inside each receptor was used as the impact variable. Then, by using flood-damage curves for the corresponding receptor typology, inundation water depth was translated to relative damage. Thus, flood-damage curves are the vulnerability relations used to quantitatively assess inundation risk. This was then translated into four levels of impact—none, low, medium, and high—which are case and receptor dependent (see the following sections). The chosen damage curves do not include uncertainties, and they are used as recommended by the Administration at each study site. This implies that damage ranges and damage-hazard relations are different and therefore, final impact levels (from none to high) are site-specific. This assumption aimed to better communicate results to local stakeholders.

The magnitude of the risk associated with erosion depends on the combination of vertical erosion and distance of erosion to the receptors. This was implemented by building multiple buffers (increasing in distance) around each receptor and intersecting them with the information ofapplying the polygon intersection formerly explained with the gridded maximum vertical erosion output from XBeach. The definition of risk categories related to erosion thresholds and distances is also site dependent, given their different morphologies.

3.4.1 Exposure and vulnerability in the Tordera Delta case study

The distribution of receptors for the Tordera Delta case study was derived from cartographic information ~~from~~ of the Catalan Cartographic Institute ~~(ICC)~~ and completed manually through ~~an~~ orthophoto analysis. The study site was divided into eight areas, of which four are located at the south of the river mouth, corresponding to the Malgrat de Mar municipality, and the other four to the north, corresponding to the Blanes municipality. These two sets of four areas were selected to enable ~~an~~ the analysis of the impact at different bands regarding their distance the limit of ~~the public domain (which separates~~ the public beach ~~from the hinterland)~~. The first band corresponds to the first 20 m of hinterland. The second band is 30 m wide and located just after the first one 20 to 50 m from the boundary of the public domain. The third covers the range from 50 to 75 m, while the fourth band covers all the hinterland omitted between the end of the third band and the inland ~~simulation~~ domain boundary. This enables an assessment of the distribution of the impacts ~~of the different scenarios~~ in terms of distance to the coastline. ~~Thus, the effectiveness of removing receptors from each of the bands considered could be assessed, which corresponds to different~~This allowed exploring setbacks as ~~DRR~~ risk reduction measures. Three groups of receptors were considered to ~~have~~ be homogeneous in terms of ~~vulnerabilities~~vulnerability, namely houses (concrete buildings), campsite elements (soft buildings and caravans), and infrastructure (promenade and road at the back of the beach). Table 2~~Table 2~~ shows the distribution of campsite elements and houses in the different areas. The infrastructural receptors (promenade at the north and road at the south) are only located in the first 20 m band (Areas 1 and 5).

Table 2: Distribution of receptors at the Tordera Delta study site.

The consequences of flooding were assessed through flood damage curves used to characterise the relative damage based only on water depth (Table 3). Data ~~(see details in Table 3)~~ was obtained from the Agència Catalana de ~~L'Aigua~~ l'Aigua (2014)~~., which derived it from FEMA (2001).~~

The relative damage values to buildings and campsite elements were converted into the level of risk as follows: (i) No impact for 0% relative damage to buildings and campsite elements, (ii) Low impact for damages below 26% to buildings and 50% for campsite elements, (iii) Medium impact when damages to buildings range from 26 to 45% and damages to campsite elements range between 50 to 70%, ~~and~~ (iv) High impact for relative damages higher than those formerly exposed for both receptors.

Table 3: Vulnerability relations for houses and campsite elements at the Tordera Delta study site with and without Flood Resilience Measures~~DRR measures~~ (FRM).

The buffers defined to assess the erosion hazard at the Tordera Delta are as follows: (i) ~~The~~ A 20 -m distance was used as a threshold from 'none' to 'low' erosion risk, and corresponds to the average beach retreat at the site for a storm with a return period of 38 years ~~(. This was used as a threshold ranging from 'none' to 'low' risk of direct impact due to erosion. The return period is~~ commonly used for infrastructural receptors similar to those in the Tordera Delta ~~(low economic importance~~ for a lifetime of about 25 years). (ii) The 12-m buffer (average retreat for the 10-year return period) was used as the threshold from low to 'medium' impact. ~~For a medium impact~~Medium impact is a post-monitoring situation~~,~~ where receptors ~~are in the post-monitoring situation and begin~~will to be exposed to the direct impact ~~of~~ for relatively frequent storms. (iii) Finally, the 3-m buffer was used as the threshold for the 'high' impact risk, meaning that the receptor is directly affected by erosion at the toe or impacted by ~~a direct~~ waves ~~in the analysed scenario~~during the storm. A buffer was considered to have been affected when ~~a~~ vertical erosion was higher than ~~threshold of~~ 50 cm ~~was imposed~~.

3.4.2 Exposure and vulnerability in the Lido degli Estensi-Spina case study

The analysed receptors belong to the central area of the model domain at approximately 600 m from the lateral boundaries (Figure 1, B2). Two main types of receptors were selected: (i) the residential and commercial buildings mainly present in the towns of L. Estensi and L. Spina, and (ii) beach concessions on the beach directly facing the sea. In this study, only receptors belonging to the seafront of Lido degli Estensi and Lido di Spina were considered, as they are mainly impacted by sea storms. Receptors were extracted from a recent Regional Topographic Map (Carta Topografica Regionale, scala 1:25000, anno 2013)~~, and the polygons were drawn in ArcGIS~~. Table 3~~Table 4~~ summarises the identified receptors. ~~Following this, the grid cells affecting each receptor were defined.~~

Table 4: Distribution of receptors at Lido degli Estensi and Lido di Spina.

The vulnerability relation for inundation hazards was defined considering a flood-damage curve from a recent study on Italian territory by Scorzini and Frank (2015). This work was based on a micro and macro-scale study of the impacts of the 2010 river flood in Veneto (Italy) on residential houses. In the current work, it was adapted and applied to the receptors of the area (see details in column A of Table 5), and relates the flood relative damage factor (~~FRDF;~~ values: 0–1) to flood depth. In particular, the worst case curve was used, which represents flood-related damages to single-family detached buildings with a basement. Although this curve is for residential buildings, it ~~is~~ was assumed the same for commercial buildings and beach concessions, as no additional and specific information was available. The curve was modified considering the ~~DRR~~ risk reduction implementation described in Section 3.5.2. The level of flood risk was defined as follows: none, when the ~~FRDF~~ relative damage is null, low, when the ~~FRDF~~ relative damage factor is higher than zero but lower than 0.1, medium, for a factor~~n FRDF~~ between 0.1 and 0.2, and high, for an ~~FRDF~~ relative damage factor higher than 0.2.

Table 5: Vulnerability relation for flooding adopted for the receptors at Lido degli Estensi-Spina without (A) and with Flood Resilience Measures (B).~~Table 5: Vulnerability relation for flooding adopted for the receptors at Lido degli Estensi-Spina without (A) and with DRR measures (B).~~

The vulnerability relation for erosion was defined for concessions only. The impacts due to the erosion hazard were defined based on a two-buffer approach for each receptor~~. The buffers were defined as follows: (i)~~: the first buffer was the receptor limits in the ground~~the footprint of the receptor~~, and ~~(ii)~~ the second included a corridor of 10 m around the receptor.
Erosion was considered present if >0.05m (vertical) and significant when >0.5m. The erosion risk categories for each receptor were set as follows: (i) Safe: no erosion in any buffer, (ii) Potential Damage: when erosion is present ~~present (>0.05 m; negligible otherwise)~~ in the 10-m buffer and/or ~~is~~ present ~~with values less than 0.5 m~~but not significant in the ~~footprint buffer~~receptor itself, and (iii) Damage: when the erosion limit of 0.5 m is exceeded ~~for~~ within the ~~footprint buffer~~receptor limits. Notably, the threshold of 0.5 m was set considering the uncertainty of the model grid topography (±0.15 m) and assuming that the foundations of the concessions are a minimum of 0.2 m thick.

3.5 Testing scenarios and ~~DRR~~ risk reduction alternatives

To compute the analysis under climate change scenarios (CCS) and under the implementation of ~~DRRs~~risk reduction measures, it was necessary to identify the variables and settings affected by each scenario, either a future projection or implementation of a ~~risk reduction~~ measure. Therefore, an appropriate approach was selected to consider these modifications in the ~~SPRC~~ methodology chain.
The CCS mainly affect the hazard and therefore, are applied in the modelling chain. The ~~DRRs~~ risk reduction measures can affect both hazard and vulnerability/exposure variables. In the following, the implementation of the CCS and ~~DRRs~~ measures is described for each case study, emphasising the affected variables and steps of the methodology. ~~All~~ The measures were pre-selected considering interviews to stakeholders, and were assumed to be ~~assessed DRRs were considered~~ fully implemented and completely effective (~~DRR~~ measure uptake and effectiveness: 100%) in all cases.

3.5.1 Climate change scenarios in the case studies

Future projections of ~~MSL~~ mean sea level were based on the AR5 RCP8.5 (Church et al., 2013). Other factors such as changes in storminess, wind speeds~~s~~, or wave highs~~s~~ were not expected to change significantly in the NW Mediterranean (Lionello et al., 2008; Conte and Lionello, 2013), and are characterised by high uncertainty in the Northern Adriatic (IPCC, 2013). Data to include the sea level rise (SLR) in the assessment of future scenarios was provided by the EC Joint Research Centre database (for further detail, see Vousdoukas et al., 2016). For the Tordera Delta study case, the time horizon of 2100 was chosen, while the 2050 projection was used for Lido degli Estensi-Spina, because the ~~SLR~~ projections in the Adriatic are more uncertain than in the NW Mediterranean. Therefore, the 2100 horizon could yield highly unreliable results.

At the Tordera Delta, the RCP8.5 estimates an increase of 0.73 m by 2100. Therefore, all 24 simulations described in Section 3.2 were repeated with the projected future ~~MSL~~sea level. Moreover, the potential beach accommodation to SLR was modelled following Bosom (2014) and Jiménez et al. (2017a). This was accomplished assuming an equilibrium coastal profile response following the Bruun rule (Bruun, 1962), resulting in landward and upward displacement of the beach profile. Dunes preserve the pre-SLR shape when there's enough accommodation space, and the shape was cut where there wasn't. The estimated shoreline retreat due to the SLR in the area is 22 m. Thus, morphological ~~coastal adaptation~~response to SLR is included in the assessment. Finally, Casas-Prat and Sierra (2012) predicted a directional change in mean sea conditions from the current dominant (E) to the secondary direction (S). This effect was ~~qualitatively~~ explored by constraining the ~~assessing~~ assessment to eastern incoming storms ~~in the CUS~~for present conditions and imposing an equal ~~likelihood~~ frequency of eastern and southern incoming storms ~~in the CCS~~for future scenarios. Therefore, three different CCS were explored: (i) CCS1: current situation (CUS)~~CUS~~ + SLR with the corresponding estimated beach accommodation; ~~(CCS1),~~ (ii) CCS2: CUS + effect of direction switch in incoming storms ~~(CCS2)~~, and (iii) CCS3: assessing the contribution of both components if occurring at the same time.~~, i.e. SLR + switch in storm incoming direction (CCS3).~~

In Lido degli Estensi-Spina, the combined contribution of the predicted SLR with the subsidence component (not negligible in the area, e.g. Taramelli et al., 2015) was implemented. The resulting value of ~~RSLR~~ relative SLR by 2050 used in the analysis is 0.30 m. ~~The forcing events' water level time-series were modified~~The position of the MSL was changed for all forcing events, ~~including~~ adding the predicted ~~RSLR~~ relative SLR by 2050 in the CCS. The morphological accommodation to the SLR was not implemented in the numerical analysis; however, ~~its effect is~~the implication of this choice is discussed in Section 5.2. In total, 24 additional simulations were run for the CCS.

3.5.2 ~~DRR~~ Risk Reduction alternatives in the case studies

Three ~~DRR~~ risk reduction measures were tested for the Tordera Delta zone (see Figure 5): (i) Receptors Setback, ~~(RSB),~~ (ii) Flood Resilience ~~(set of)~~ Measures, ~~(FRM),~~ and (iii) Nourishment + Dune ~~(N+D)~~.

The ~~RSB~~ Receptors Setback measure affects the exposure of the receptors. It entails removing all receptors inside a defined band measured from the public domain coastal limit (the limit between the back of the beach and hinterland). Three scenarios of the setback were simulated: 20 m, 50 m, and 75 m.

The Flood Resilience Measures ~~FRM~~ affect~~s~~ the vulnerability of receptors so that for a given water depth, the expected impact ~~on campsites and houses during an inundation~~ event decreases ~~from the current situation~~ when the ~~DRR~~ measure is implemented. It ~~is~~ was assumed that resilience measures such as raised electricity outlets and utilities, adapted flooring, resilient plaster, and waterproof doors and windows were installed in all houses and campsite elements. This measure was implemented by assuming a modified damage curve as shown in Table 4.

Finally, the N~~+D~~ourishment + Dune changes the pathway and affects the inundation/erosion hazard. It includes beach nourishment at the south of the river mouth to increase the beach width by 50 m over 1 km~~ at the south of the river mouth~~, where the highest erosion occurs. In addition, the level at the top of the beach was increased on both sides of the river mouth, with non-erodible sandbags at the northern side, where the campsites are closer to the coastline, and a sandy dune at the southern side. At both sides, the final height of the protective measure was +4.8 m ~~in terms of~~from the ~~MSL~~MSL. Since this measure affects the pathway, ~~24 extra simulations,~~ this measure ~~was~~ had to be implemented in the XBeach grid. Thus~~,~~ the 48 storms (24 CUS, 24 CUS+SLR) ~~were needed, and another 24 to combine the implemented measure with the CCS~~were simulated again with the edited morphology.

Figure 5: ~~DRR~~ Risk reduction measures at Tordera Delta. ~~Coastal~~ Receptor setbacks (20, 50, and 75 m) and ~~Infrastructural Defence~~ Nourishment + Dune (beach nourishment at Malgrat beach + artificial dune at S'Abanell and Malgrat beaches).

The selected ~~DRR~~ measures tested for the Lido degli Estensi-Spina case study were: (i) a Winter Dune ~~(WD)~~ system, affecting both flooding and erosion impacts, and therefore the hazards modelling process; and (ii) ~~a set of FRM~~Flood Resilience Measures, influencing the flood vulnerability relations of receptors.

The ~~WD~~ Winter Dune (see Figure 6) is a common ~~DRR~~ risk reduction practice along the Emilia-Romagna coast, especially in the Ravenna province (Harley and Ciavola, 2013), and regularly implemented by local concessionaires without a scientifically based design criterion. It consists of a set of embankments built on the beach in front of concessions through beach scraping or sand replenishment (less frequent option). This ~~DRR~~ risk reduction measure was implemented in the ~~process-oriented module (XBeach)~~XBeach model. The ~~WD~~ Winter Dune was designed as a continuous dune that protects more than one concession, introducing breaks in the continuity of the feature where natural/human obstacles or passages were located. The top of the ~~WD~~ dune was fixed at 3 m above the ~~MSL~~ MSL and the width (at the top) at 10 m. The ~~WD~~ dune was integrated in the model modifying the bed levels through the Dune Maker 2.0 tool (Harley, 2014). Both the CUS and CCS were tested with ~~the DRR WD~~this measure adding 48 additional simulations.

The ~~FRM~~ Flood Resilience Measures decrease~~s~~ the receptor's physical vulnerability to floods. It was assumed that the effective application of these measures would decrease the damages ~~(FRDF >0.1)~~ for water levels lower than a certain threshold, assumed here as 0.7 m (e.g. all electrics have to be placed above the threshold). This assumption was integrated in the analysis by modifying the selected depth-damage curve, as defined in column B of Table 5, and included in the BN. Considering the adopted definition of flood risk levels (see Section 3.4.2), the ~~FRM~~ measure results in a complete obliteration of receptors for the medium flood risk, therefore increasing the receptors at the low level and not affecting receptors at high risk.

Figure 6: Artificial winter dunes in Emilia-Romagna: A) Winter dune in Porto Garibaldi (Comacchio, Italy); B) Building of a winter dune by beach scraping at Lido di Dante (Ravenna, Italy) (Harley, 2014); C) Representative model profiles at Lido di Spina north (original: black solid line; with winter dune DRR: red dashed line).

3.6 Bayesian network ~~DSS~~for decision making.

BNs use probability theory to describe the relationships between many variables, and can evaluate how the evidence of some variables influence other unobserved variables. For example, evidence could be a forecast of the source variables characterising an impending storm. On the other hand, local hazards and damages in the coastal area have not yet been observed, but can be predicted with the BN. The model can also be updated with artificial evidence to explore extreme event scenarios or investigate the potential of ~~disaster~~ risk reduction plans.

A BN is based on a graph (Figure 7). It consists of nodes connected by arcs that represent random variables and the potential influences between them. The direction of the arcs is crucial for the probabilistic reasoning algorithm of the BN, but does not necessarily indicate causality. For any two variables connected by an arc, the influencing one is called a parent, while the one influenced is referred to as the child. Thus, in Figure 7, X1, X2, and X_3 are the parents of X_4. A simple way to parameterise a BN is to discretise continuous variables after defining their data range, and to specify conditional probability tables for each node. The authors adopted this approach. The conditional probability tables indicated how much a variable could be influenced by others. Mathematically, the graph structure and conditional probability tables define the joint distribution of all variables in the network, $X_1, ..., X_n$, based on the factorisation of conditional probability distributions (Eq. 1):

$$p(X_1, \ldots, X_n) = \prod_{i=1}^{n} p\big(X_i \big| pa(X_i)\big), \qquad (1)$$

where pa(Xi) are the parents of node Xi (Pearl, 1988; Jensen, 1996). Once the joint distribution has been defined, the effects of any evidence can be propagated with efficient algorithms throughout the network (Lauritzen and Spiegelhalter, 1988).

Figure 7: BN graph with four nodes.

In the RISC-KIT project, a generic structure for a BN that can support decision-making in coastal risk management was proposed. This structure is based on the ~~SPRC~~ source-pathway-receptor-consequence and has five components (node types): source boundary condition~~ (BC)~~, hazard~~ (H)~~, receptor~~ (R)~~, impact/consequence~~ (C)~~, and ~~DRR~~ risk reduction measure~~ (M)~~. Typically, each component includes several variables. Panel (IV) in Figure 4 shows their influence on each other. In general, all boundary conditions influence all hazards, as indicated by the solid arc in Figure 4. ~~Differently, each~~Each type of receptor (e.g. people, buildings, infrastructure, and ecosystems) ~~has a sub-module in the BN consisting of an R node~~is represented by a node where different areas are the different bins (representing the locations of receptors on the site). Receptor nodes are also connected to~~,~~ hazard~~H~~ nodes (representing the hazards given the locations of the receptors), and ~~C~~ both at the same time are connected to the consequence nodes (representing the consequences ~~given (some of) the hazards for the receptors~~to a given receptor and location). The dashed arcs in Figure 4 represent the fact that the sub-modules are not directly interconnected. Nevertheless, dependencies arise from the common parents, which are boundary conditions and possibly ~~DRR~~ risk reduction measures.

Alongside the generic structure, ~~it also provided~~ a c++ programme that automatically creates the BN (https://github.com/openearth/coastal-dss) is also provided. As input, the programme requires variable definitions and land use data, vulnerability relationships, and a 2D gridded simulation output of numerical physical process-based models of hindcast or synthetic extreme event scenarios. Essentially, the programme extracts the values of hazard variables from the simulation output at the locations of every individual receptor so that we could obtain hazard distributions for each receptor type. Because each simulation contains the coastal response to one storm scenario under a set of ~~DRR~~ measures, the distributions are conditional and can be stored directly as entries of the conditional probability tables associated with each hazard node. Being parents of the hazard nodes, boundary conditions and ~~DRR~~ risk reduction measures define the dimensions of the conditional probability tables. By simulating those storm scenarios that correspond to all possible value combinations, the tables are completely filled. In the final step, the conditional hazard distributions were transformed to conditional impact distributions with vulnerability steps.

3.6.1 BN implementation at the case study sites

The schemes of the BNs implemented for the Tordera Delta and Lido degli Estensi-Spina case study sites are shown in Figure 8 and Figure 9 respectively. The nodes (circles) define the variables of the network, while arcs (arrows) show the relations between the variables. The ~~BC~~ boundary conditions ~~is~~ are the blue nodes, and the location and distributions ~~(R)~~ of the receptors are the grey nodes. ~~These nodes~~Both affect those in dark orange, which refer to the receptors' hazards ~~(H)~~. The hazard was then transformed through the vulnerability relations into consequences ~~(C)~~, which are represented by the light orange circles. The measures' nodes ~~(M)~~ are indicated in green and can affect ~~the H, C, or R nodes~~different node types depending on the effect (by definition) of the measure.~~.~~ The structure is very flexible and can be applied at different coastal settings. The scheme can be adapted with different boundary conditions, hazards, receptors, consequences and measures depending on the needs driven by research and/or coastal management objectives. It follows that, for very similar coasts, or even for the same case study, the scheme can differ. The bin ranges for variables characterising boundary conditions is selected to be equidistant covering the observed values at each study site (Table 1). Additional non-observed ranges are introduced to account for SLR. The used number of intervals is a compromise between accuracy and computational effort. Each combination showed in Table 1 has been simulated twice to account for potential variability inside bins. Then, all simulations are repeated for DRR scenarios affecting hazards (i.e. Winter Dune and Nourishment + Dune). Therefore, a total number of 96 model runs were required for the applied bin set-up. As a reference, using parallel simulations with 48 threads, the ratio computation time over real storm time was ~0.2, meaning that a 40 hr storm takes ~8 hours of simulation time.

Figure 8: Bayesian Network scheme for the Tordera Delta site.

Figure 9: Bayesian Network scheme for the Lido degli Estensi-Spina site.

4 Results

In this section, the results of scenario testing are provided for each case study through an integrated comparison of percentages of receptors at each level of flooding and erosion risks. This is done by comparing the risk levels under current and climate change scenarios with and without measures. In any case, it has to be taken into account that this assessment does not include the statistical distribution of storm variables. We assume that there is no prior knowledge on their distributions and, as consequence, we simply describe them with a uniform distribution. This approach is adequate to explore scenarios and to assess the efficiency of protection measures in terms of impact reduction.

In this section, the results of scenario testing are provided for each case study through an integrated comparison of computed risk levels in terms of percentages of receptors at each level of risk for flooding and erosion for each type of receptor and relevant location in the CUS and CCS. The DRR impacts are shown by comparing the risk levels in the CUS and CCS with those computed in each scenario with the implemented DRR.

4.1 Tordera Delta

The results assessment was performed separately for both sides of the river at s'Abanell beach at the north and Malgrat beach at the south. The inundation impact assessment considered all receptors at the study site whereas the erosion analysis focussed only on the first 20-m band of hinterland because the only receptors exposed to an erosion hazard are located in that area.

The results of the flooding impacts, here presented for campsite elements, on campsite elements and houses (Figure 10 to Figure 13) indicate that under current conditions, in the CUS (E incoming storms with current MSL), campsite elementsreceptors at both sides of the river mouth are expected to suffer the same magnitude of damages: 80–83% of elements will be safe, while only 2–3% of the elements are under high-impact risk (Figure 10). The situation differs slightly when assessing houses (Figure 12), since more damages are expected to occur south of the river mouth (20% of elements are at low risk and 2% at medium risk), rather than in the northern domain (2% at low risk and 1% at medium risk).

Under climate change scenarios, When assessing the CCS, results demonstrate a different behaviour at each side of the river mouth is detected. Southwards of the river mouth, the beach is highly sensitive to both changes in storm direction and SLR (Figures 10 and 11). Thus, when CCS3 conditions are analysed in Malgrat, the BN indicates that 69% of campsite elements are affected, with 41 % being at high risk. On the other hand, the beach at the north (S'Abanell) is highly sensitive to In S'Abanell, the SLR significantly increases the impacts of flooding (CCS1, Figure 10) but it is not affected by a potential change in storm direction, whereas the directional shift of storm direction (equal frequency of E and S incoming storms) does not increase any of the receptors at risk (CCS2 and CCS3, Figure 11). In the CCS1, the impact on campsite elements increases from 17% to 37% of affected receptors. Campsite elements expected to suffer high impacts increase from 2% to

~~14%. However, expected impacts under CCS2 are similar and even lower than those observed under the CUS, and the results obtained for CCS3 are comparable to CCS1 for the northern domain.~~

~~On the other hand, south of the river mouth, the response to CCS is equally sensitive to changes in storm incoming direction than to SLR. In fact, 50% of houses and 56% of campsite elements are affected by some level of impact under CCS1 (Figure 10 and Figure 11), while 38% of houses and 40% of campsite elements are affected under CCS2 (Figure 11 and Figure 13). Therefore, when CCS3 conditions are tested south of the river mouth, the outcome obtained from the BN shows that 63% of houses (34% at medium risk) and 69% of campsite elements (41% at high risk) are affected.~~

Figure 10: Distribution of campsite elements at every level of flooding risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a ~~DRR~~ risk reduction configuration ('None': no ~~DRR~~ measure implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).

Figure 11: Distribution of campsite elements at every level of flooding risk. Top-left: climate change scenario 2 (50-50% east-south storms) at S'Abanell; Top-right: climate change scenario 3 (50-50% of east-south storms + SLR) at S'Abanell; Bottom-left: climate change scenario 2 (50-50% east-south storms) at Malgrat; Bottom-right: climate change scenario 3 (50-50% of east-south storms + SLR) at Malgrat. Each bar in a panel represents a ~~DRR~~ risk reduction configuration ('None': no ~~DRR~~ measure implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).

Comparing the effectiveness of the ~~DRR~~ risk reduction measures highlights ~~N+D~~Nourishment + Dune as the most effective ~~measure~~ one against flooding under current and climate change scenarios~~for the CUS and all tested CCS~~. As expected, the effectiveness is higher in Malgrat than in S'Abanell, as beach nourishment is located only south of the river mouth ~~and~~ whereas the dune is present on both sides. It was observed that all significant impacts (medium and high) to receptors under ~~the CUS~~current scenario were removed for both sides of the river. Moreover, at ~~the~~ Malgrat ~~domain~~, the number of affected receptors was reduced by ~~19%–22~~~20% for the CUS, CCS1, and CCS2 scenarios, and ~~40–46~~~40% under CCS3.

The implementation of the ~~FRM~~ Flood Resilience Measures was effective in terms of preventing high impacts on any receptor, but did not significantly reduce the total number of receptors affected by some level of risk. The magnitude of reduction of receptors at risk was ~9%. It should be mentioned that this is a theoretical measure, as we assumed that ~~the FRM are~~it is properly designed, implemented and 100% effective for site conditions.

~~**Figure 12: Distribution of houses at every level of flooding risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a DRR configuration ('None': no DRR implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).**~~

~~**Figure 13: Distribution of houses at every level of flooding risk. Top-left: climate change scenario 2 (50-50% east-south storms) at S'Abanell; Top-right: climate change scenario 3 (50-50% of east-south storms + SLR) at S'Abanell; Bottom-left: climate change scenario 2 (50-50% east-south storms) at Malgrat; Bottom-right: climate change scenario 3 (50-50% of east-south storms + SLR) at Malgrat. Each bar in a panel represents a DRR configuration ('None': no DRR implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).**~~

Finally, three ~~RSB~~ Receptors Setbacks were tested: 20 m ~~(20SB)~~, 50 m ~~(50SB)~~, and 75 m ~~(75SB)~~. The results indicate that only the 75- m setback demonstrated a risk reduction magnitude comparable to ~~infrastructural defence~~Nourishment + Dune; however~~, in most cases~~, the efficiency of the Nourishment + Dune was in general higher than the managed retreat. Only in S'Abanell, with higher topography and where the measure only consists of a ~~only~~ dune without nourishment, a greater risk reduction was achieved through the 75 m setback~~SB~~.

Results for the erosion impact risk assessment showed similar results for the three analysed receptor categories and no significant differences between CUS-~~CC1~~ CC2 and ~~CC2~~CC1-CC3 respectively. For simplicity, results related to ~~Campsites (Figure 14) and~~ Infrastructure (Figure ~~15~~12), for the CUS and CC1 scenarios are provided in the following.

~~**Figure 14: Distribution of campsite elements at every level erosion risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a DRR configuration ('None': no DRR implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).**~~

Figure 12: Distribution of Infrastructures at every level erosion risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a risk reduction configuration ('"None'": no measure implemented; '"N+D'": Nourishment and Dune; '"FRM'": Flood Resilience Measures; '"20SB, 50SB, and 75SB'": 20 , 50, and 75 m setbacks, respectively).

Under the CUS, ~~23% of campsite receptors (Figure 14) in s'Abanell and 8% in Malgrat are at low risk, whereas only 1–2% demonstrate a medium risk in both areas. The CCS indicated that the level of erosion risk increases much more when the SLR increases than for the directional switch of incoming storms on both sides of the river mouth. In the CCS1 scenario, receptors located in s'Abanell at medium risk increase to 30%, while 5% are at high risk. In Malgrat, the same scenario results in 20% of campsite elements being at medium risk and 14% at high risk. On the other hand, the CCS2 scenario does not imply a significant difference for the CUS and similarly, the impacts in CCS3 are comparable and lower than those obtained for CCS1.~~

~~Focusing on the infrastructural receptors (Figure 15),~~ the promenade at the north of the river mouth is ~~currently~~ at significant risk (70% at medium risk and 13% at high risk), whereas the road in Malgrat is potentially safe. In the CCS1 scenario, the assessment highlights that because of the increase of ~~MSL~~ sea level and corresponding morphological accommodation, the percentage of promenade under high risk and therefore direct erosion at the toe increases up to 33%, with some impact appearing on the road in Malgrat.

Figure 15: Distribution of Infrastructures at every level erosion risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a DRR configuration ('"None'": no DRR implemented; '"N+D'": Nourishment and Dune; '"FRM'": Flood Resilience Measures; '"20SB, 50SB, and 75SB'": 20 , 50, and 75 m setbacks, respectively).

The assessment of the efficiency of the DRR measures regarding erosion indicates that the N+DNourishment + Dune does not have any a significant impact on reducing risk. In fact, in some scenarios, the number of affected receptors at low risk seems to increase, because of the indirect effect of alongshore change in erosion/accretion patterns caused by the measure. In addition, the beach nourishment is regularly washed out in severe storm conditions. In the case ofThe only case where the nourishment plays some protective role is at the road in Malgrat, the nourishment is placed in a position with higher local erosion rates; thus, where, the measure prevents the impact in CCS1. On the other hand, RSB Receptor Setback is 100% effective in dealing with the impact of erosion, and the a 20SB 20 m retreat (measured from beach limit in current conditions) is enough to cope with risk under the present situation and for all future projected conditions at both sides of the river mouth.

4.2 Lido degli Estensi-Spina

The overall results for the risk of flooding for residential and commercial buildings located in the towns of Lido degli Estensi and Lido di Spina are provided in Figure 15. The overall results for flooding and erosion risks on concessions are shown in Figures 16 13 and Figure 1714, for flooding and erosion risks respectively..

The CUS for residential and commercial buildings (Figure 15) evidenced that most receptors in Lido degli Estensi-Spina are safe from flooding impacts, with the exception of the 2% at low risk in Lido degli Estensi. In the CCS, the receptors at low risk increased in Lido degli Estensi to 10%, while 1% were at medium risk. The increase in receptors at low risk is more limited in Lido di Spina (5%). The WD demonstrated a positive effect on receptors' level of risk. In particular, under the CCS, it decreased the receptors at low risk by almost 10% of the total. The effect of FRM is limited to the CCS at Lido degli Estensi, where the receptors at medium risk were reclassified at a low level.

Figure 16: Distribution of residential and commercial buildings for every level of flooding risk. Top left: current scenario at Lido degli Estensi; Top right: climate change scenario at Lido degli Estensi; Bottom left: current scenario at Lido di Spina; Bottom right: climate change scenario at Lido di Spina. **Each bar in a panel represents a DRR configuration ('None': no DRR implemented; 'WD': Winter Dune; 'FRM': Flood Resilience Measures).**

Focusing on the flooding risk for concessions (Figure 1613), the CUS evidenced noticeable impacts, with Lido di Spina presenting the larger . At Lido degli Estensi, almost 30% of receptors were categorised at low risk and 15% at medium risk. In comparison, at Lido di Spina, the number of receptors at risk and with higher intensityincreased in number and intensity. The results showed that 27% were at low risk, 25% at medium risk, and 6% at high risk of flood. The CCS presence of a climate change scenario exacerbated exacerbates the expected impacts for both locations. At Lido degli Estensi, the concessions at low risk increased to 50%, those at medium risk remained stable, but 8% of receptors were at high flooding risk. Similarly, at Lido di Spina, the percentages of concessions categorised at risk increased to 34% at low risk, 33% at medium risk, and 20% at high risk.

The Winter Dune system had a positive impact in all cases, with the number of for both the CUS and CCS. At Lido degli Estensi, the concessions at risk decreased decreasing from 44% (29% at low and 15% at medium risk) to 10% (only low risk) of the total for the CUSat Lido degli Estensi and . The same scenario for Lido di Spina demonstrated limited impacts (13% at low and 3% at medium risk at Lido di Spina) for concessions when the WD was implemented, while the total receptors at risk without DRR was 58%. This measure was also effective to reduce the risk under the climate change scenario.The impacts on the CCS also decreased with the WD compared to the scenario without DRR. For Lido degli Estensi, where previously more than 60% of concessions were at risk, 8% of the receptors were at low risk and 14% at medium risk. At Lido di Spina, the positive effects of the WD system increased the percentage of safe receptors from 13% to 59%, thus decreasing the concessions at risk (26% at low, 6% at medium, and 9% at high flooding risk).

The FRM Flood Resilience Measures had positive effects on impacts by moving all receptors at medium risk to the low risk category. In particular, under the CUS, the concessions at low risk increased from 29% to 44% and from 27% to 52% at Lido degli Estensi-Spina respectively. For the CCS, the same results increased from 50% to 65% at Lido degli Estensi, and from 34% to 67% at Lido di SpinaHowever, by definition, it had no effect on lowering the fraction of receptors presenting, in the current situation, low and high levels of risk.

Figure 1713: Distribution of concessions for every level of flooding risk. Top left: current scenario at Lido degli Estensi; Top right: climate change scenario at Lido degli Estensi; Bottom left: current scenario at Lido di Spina; Bottom right: climate change scenario at Lido di Spina. Each bar in a panel represents a DRR risk reduction configuration ('None': no DRR measure implemented; 'WD': Winter Dune; 'FRM': Flood Resilience Measures).

With respect to erosion-induced impacts, obtained results indicate a lower level of risk than the identified for flooding, with only theThe risk assessment results related to coastal erosion (Figure 17) showed the potential level of damage of risk under the CUS: 8% and 14% of concessions being at risk at Lido degli Estensi- and Lido di Spina respectively (Figure 14). These percetanges increase up toIn the CCS, the previous results increased to 11% and 30% respectively when the climate change scenario is considered. Notably, 1% of the concessions in Lido degli Estensi were indicated as being possibly damaged.

The effectiveness of the Winter Dune system as a risk reduction measure is demonstrated by the observed decrease in the number of positive effects on the potentially damaged concessions at Lido di Spina under both climate scenarios. However,the CUS by decreasing the receptors at potential risk from 14% to 5%. In contrast, at Lido degli Estensi, this measure increases the number of potentially damaged receptors. receptors increased from 8% to 13% when implementing the WD DRR. This negative effect also occurred in the CCS. At Lido degli Estensi, the receptors at potential risk increased to 17%, while damaged receptors remained stable. At Lido di Spina, the WD had a contradictory effect. It decreased potentially damaged receptors to 14% and increased damaged concessions to 2%. Simulation results show that when the dune is present with concessions close at its rear, and the storm overcomes the measure, water arrives with enough velocity to produce scouring at the first concessions.

Figure 1814: Distribution of concessions for every level of erosion risk. Top left: current scenario at Lido degli Estensi; Top right: climate change scenario at Lido degli Estensi; Bottom left: current scenario at Lido di Spina; Bottom right: climate change scenario at Lido di Spina. Each bar in a panel represents a DRR risk reduction configuration ('None': no DRR risk reduction implemented; 'WD': Winter Dune; 'FRM': Flood Resilience Measures).

A further step in the analysis of risk scenarios was undertaken using the BN in reverse mode, i.e. to showlooking at the distribution of the boundary conditions that generategiven a certain distribution of flood damage to concessions at Lido degli Estensi-Spina, both with and without Winter Dune in the configuration without and with the WD DRR. Flood damage to concessions is constrained in the BN to equal fractions of low, medium and high risk. This can be understood as a qualitative scenario were all receptors suffer some damage, and the intensity of the damage is uniformly distributed. The BN enables assessing the distribution of boundary conditions related to an impact scenario where all receptors suffer consequences uniformly for all risk levels (i.e. all receptors are affected by flooding at least at a low level of risk). The results of this analysis are shown in Figure 18 for the CUS, with (Figure 18, green bars) and without the WD DRR (Figure 18, red bars). The graph on the left shows the distribution of the TWL and the Hs on the right. outputs the fractions of boundary conditions which are likely to produce the constrained impacts, according to the introduced data.

Notably, under current scenario and the CUS without DRRmeasure, the Hs is distributed more uniformly (values ranging from 15% to 31%) compared to the TWL (Figure 15), which demonstrated demonstrates a strong increasing tendency. to increase (values ranging from 10% to 58%). This indicates that compared to wave conditions, the water level is the main driver for flood impacts.

The results for the WD DRRWinter Dune scenario showed that the most probablelargest fraction of conditions leading to flood damages to concessions are TWL>1.45 m (93%) and Hs>4 m (4<Hs<5 m: 47%; 5<Hs<6 m: 43%). These results indicated that the WD DRR in the CUSWinter Dune can is effective to minimise the consequences of coastal storms with TWL<1.45 m and Hs<4 m in the current situation.

Figure 1915: Distribution of boundary conditions (TWL on the left and Hs on the right) that generatefor constrained uniform flood damages in the current scenario for Lido degli Estensi-Spina. The configuration without DRR measures (green bars) and for the implementation of the WD DRRWinter Dune (red bars) were compared.

The same analysis was performed for the CCSWhen the analysis was performed under the climate change scenario (Figure 16) , as shown in Figure 19. In this case, the scenario situation without DRR measure demonstrated an even less dominant lower influence of TWL Hs (ranging from 24% to 40%) on flood consequences to concessions, even if still stronger than the Hs,since a more uniform distribution of this variable is obtained. and an almost uniform distribution (all bins around 25%).

As expected, the relative ~~R~~SLR (+0.3 m; RCP8.5 by 2050) increased the risk of lower intensity storms. Thus, in general, under the CCS, all storm combinations generated flood consequences to concessions.

The results for the ~~WD~~ Winter Dune in the ~~CCS~~ climate change scenario showed that ~~the most probable condition leading to flood damages to concessions is when TWL>1.45 m (75%) in combination with Hs>4 m (4<Hs<5 m: 35%; 5<Hs<6 m: 33%). Thus, under the CCS,~~ the influence of the ~~WD~~ dune system is less effective than in ~~the CUS~~current conditions. ~~Indeed, l~~Lower intensity storms can ~~still~~ now lead to flood damages to concessions (TWL<1.45 m: 25%; Hs<4 m: 32%). This explains the observed decrease in effectiveness of the measure in future conditions when compared to present conditions.

Figure ~~20~~16: Distribution of boundary conditions (TWL on the left and Hs on the right) ~~that generate~~for constrained uniform flood damages in the climate change scenario for Lido degli Estensi-Spina. The configuration without ~~DRR~~ measures (green bars) and under the implementation of the ~~WD DRR~~Winter Dune (red bars) were compared.

5 Discussion

The ~~aim~~ framework of the present work is appropriate for the prevention phase of the disaster management cycle. In this context, it has been applied to support decisions ~~The tool was applied as a DSS~~ for coastal risk management by facilitating intercomparison of~~, and therefore used for comparison purposes to support the assessment of DRR~~ risk reduction strategic alternatives. This comparison was performed for a large set of simulations, covering many (current and future) conditions and multiple hazards. The presented work is part of a larger investigatory process (see Martinez et al., 2017) where stakeholders and end-users were interviewed to select possible measures for critical coastal areas (i.e. local scale). The objective of the present work was to provide rather simple information on the efficiency of measures to be used in a participatory process (see Barquet and Cumiskey, 2017) aiming at selecting acceptable measures to be applied as part of an integrated local strategy for risk reduction.

~~Notably, the~~ The analysis has some inherent uncertainties associated with the implementation of the steps of the ~~SPRC~~ source-pathway-receptor-consequence model which are identified and discussed in what follows.

With respect to the definition of sources, the BN has been built by chosen storm variables limited to those previously identified as the most important to control the magnitude of storm-induced hazards at each site. Once identified, they were discretized in equal intervals covering the whole range of so far observed values. We have used a limited number of combinations to cover the most important storm classes in terms of induced hazards and damages (Armaroli et al., 2009, 2012; Mendoza et al., 2011). Increasing the number of storms will allow to better reproduce the inherent climate variability and to characterize better this source of uncertainty in the assessment. In spite of this, used values can be considered as representative for forcing conditions in both areas and, in this sense, they will allow to use the framework to assess the efficiency of tested measures to reduce inundation and erosion risks for each given conditions. No prior knowledge of storm characteristic variables was assumed, representing them with uniform distributions. This was enough to communicate scenarios and measure efficiencies to stakeholders by integrating the BN in a multicriteria analysis such as in Barquet and Cumiskey (2017). In such multicriteria assessments, BN output is combined with information on additional elements required for decision making such as economics, endurance, ecological, stakeholders' perception, allowing for the final evaluation of alternatives. As it has been mentioned before, the next step should be to reproduce the local maritime climate to analyse this performance taking into account the relative frequency of each condition. In addition, using time series data on real historical events would reduce the uncertainties introduced by representing events with synthetic design shapes.

Uncertainties associated with the pathway are related to the selection of the process-oriented models used to simulate induced hazards. In the current analysis, we have not considered this source of uncertainty since the framework is applied by using previously selected models and recommended damage curves. As it was mentioned in the method section, the selected model to simulate storm-induced hazards is XBeach (Roevilnk et al. 2009), which is currently one of the most applied at the international level. Applied model setting has been selected for each case study based on local calibrations and validations for selected storm impacts. This step has to be done prior to BN development since it will control the accuracy of estimated hazards intensity and it is also a source of uncertainty. In any case, the methodology can easily deal with this source of uncertainty if simulations from multiple models or model settings are used to feed the BN.

Another point to be considered is that this assessment framework has just been designed to analyse the storm-induced coastal response. This implies that used models do not forecast the coastal morphology at a given time (where it should be necessary to couple all governing processes) but predict the expected storm-induced changes for a given coastal configuration. As storm-induced hazards depend on existing morphology at the time of the impact (e.g. Cohn and Ruggiero, 2016), the initial morphology used in the model is also a source of uncertainty. To overcome this, a long/medium term morphological model (Hanson et al. 2003; –Lesser et al. 2004) could be used to forecast the future coastal morphology under a given climate scenario at a given time and then, to use it as the initial configuration to assess storm-induced changes. This has been illustrated here by considering the change in estimated risks due to sea level rise in Tordera Delta. This approach can also be applied to assess the effects of consecutive storm impacts (Coco et al. 2014) by using estimated post-storm bed levels as pre-storm morphology for given storm combinations. Once this extra information is included in the BN, the uncertainty associated to future shoreline configurations on assessed risks can be analysed.

Regarding receptors, their location and typology have little associated uncertainty. Houses, promenades and fixed elements were derived from accurate land use and cadastral data available for the sites. Moreover, campsite elements were manually located and delimited from available GIS-based tools and raster imagery. In spite of this, some uncertainty remains, associated with the mobility of campsite elements between seasons as well as to land-use changes or new developments. In the case of temporary elements, the worst case scenario was assumed, i.e. they are assumed to be present at any space allocated to them. This implies that we are estimating the maximum potential damage. This could be modified by considering the existing time-lag between intensive tourist use of beaches (and consequently in campsites or concessions) and storms seasonality (e.g. Valdemoro and Jiménez, 2006). The existing lag can be used to modify/reduce the exposure of this temporary elements to storm impacts.

With respect to the consequences, expected damages due to inundation have been estimated by using damage curves. Although this is a standard approach for this type of analysis (see e.g. Penning-Rowsell et al. 2013), used damage curves have been recommended by ACA (2014) and Scorzini and Frank (2015) for river flooding in Catalonia and Italy respectively. The absence of specific damage curves estimated for analyzed process and existing elements also introduces uncertainty, although in this case, it is already assumed by the corresponding administrations since they are the recommended to be used. The equivalent for expected damages due to erosion was set in terms of an erosion buffer, which represent the protective function of the beach against the direct impact of waves. As it was previously shown, this buffer was selected specifically for each site and, similarly to damage curves, it has to be defined according to local conditions.

Regarding the inclusion of the risk reduction measures in the analysis, it is assumed that protective strategies are completely and efficiently implemented when storm events occur. In the case of flood resilience measures, this implies that all existing elements in each site (from campsites to buildings) implemented flood-proofing measures. However, local social and economic conditions will influence its real implementation (see e.g. Bubek et al. 2013) and, in any case, this assumption clearly overestimate its efficiency.

When setback definition and retreat is the adopted strategy, it has to be considered the previously mentioned approach to characterize the initial coastal morphology. This implies that the effectiveness of the retreat is just measured with respect to the storm reach. To be efficient in time, the existence of any additional mid- long-term background erosion, as it is the case of the Tordera site (Jiménez et al. 2007b), should be included to properly define the required setback (e.g. Sano et al. 2011).

This also applies to infrastructural measures which are considered to be implemented at the time of the storm impact. In the case of the combined nourishment-dune solution considered in the Tordera case, this would imply that to maintain its efficiency in time, the beach would have to be renourished after each storm impact to maintain the 50 m increase in beach width. This also affects the efficiency of the winter dune tested in the Italian case, which strictly depends on the beach width before the storm impact. In this sense, Harley and Ciavola (2013) indicate that the dune height and crest width required to protect the area should be designed differently for different coastal stretches along the study area. From the coastal manager standpoint, this implies that to properly assess their performance in the future, background processes must be considered to account additional losses in beach nourishment in the Tordera (e.g. Jiménez et al. 2011) or in beach width variations along the Italian case (Armaroli et al. 2012).

Assessed risks under current conditions at both locations are consistent with already observed impacts. At the Tordera site, erosion and overwash problems are the main issue for campsites and existing infrastructures (Jiménez et al., 2011; 2017b). At the Italian case, flooding is the dominant hazard with assessed impacts being comparable with previous observations (e.g. Perini et al., 2016).

As a result of the combination of hazard and site characteristics, a notable increase of the assessed impacts is predicted for both sites when SLR is considered. At the Tordera delta, overall results indicate a doubling of expected flooding impacts. Moreover, erosion impacts will increase even further since the induced retreat will immediately imply an increase in receptor exposure. This behaviour is similar to the observed increase in damages due to the present background erosion, where campsites located in unprotected areas have been progressively losing space at the seaward boundary, and the existing promenade has suffered frequent damages during the last decades (Jiménez et al., 2011). At the Italian case study, SLR effects are mainly identified in flooding risks which will be significantly larger at the two studied areas. On the other hand, although erosion risks will also increase, they will remain relatively low. This lower increase reflects the effect of including or not the morphological response to SLR since, in this case, the future scenario was only characterized by increasing the position of the MSL.

When considering SLR-induced effects on time evolution of storm-induced risks, we have to take also into account existing uncertainties. Thus, the first uncertainty is related to the magnitude of the change itself. Here we have used the RCP8.5 SLR scenario but other scenarios could be possible (Church et al. 2013). The other source of uncertainty is controlled by the way in which this forcing is translated to the system. In this work we have assumed the Bruun rule to be valid and it was used to generate a morphological accommodation of the Tordera Delta site to SLR. Since there is no consensus on the best model to simulate this effect, other existing models and approaches (see e.g. Le Cozannet et al. 2014) could be tested and integrated in the BN to include this uncertainty. In any case, the effect of the uncertainty on the SLR projections may be larger than their associated morphological response.

In spite of the above mentioned sources of uncertainty, this analysis has permitted to identify which are the most harmful conditions to induce storm-induced inundation and erosion risks at the two study sites, to identify which are the most affected receptors and, to compare the efficiency of different risk reduction strategies. This has been done taken into account both hazards in a separated manner which is an advantage for the manager since damage induced by erosion and inundation differ in characteristics and they need to be afforded in a specific manner. Although this can be a valuable tool for decision making in storm-induced risk management, it has to be further complemented with a similar analysis including the reproduction of the statistical structure of storms in combination with a socio-economic valuation such as multicriteria analysis to properly make final decisions. In this sense, this analysis can be used as the first step to identify the most relevant risks and strategies to be further tested.

~~The authors highlight that the presented framework (Jäger et al., 2017) has demonstrated flexibility. As such, the authors are currently investigating its application to other types of risks (i.e. rock falls, landslides, etc.). In addition to the use as DSS, the tool has the potential to be applied as an EWS (Plomaritis et al., 2017) once it is properly validated. However, for that purpose, more focus on the validation of the model chain is needed.~~

~~In the following sections, uncertainties and limitations of the application of the tool at both study sites are presented and discussed alongside the obtained results.~~

~~5.1 Tordera Delta~~

~~The methodology starts with the Source characterisation and variable range definitions. In this work, a first test to check the method was presented, and a balance between computational expense and accuracy pursued. However, the way the bins were selected affects the accuracy of the output of the BN. Some input parameters have a wide range (~30-hour steps in duration~~

and only 2 main wave directions) and more simulations are desirable for a better representation of the variability of the results inside each bin. Alternatively, a higher bin resolution could be tested at the expense of a significant increase in computational efforts. The tested combinations provide a representative picture of the coastal response of the site and effectively describe the input-output relations meant to be captured in the BN. Larger amounts of forcing time series would better represent the schematisation for all combinations of storms, reducing those represented through synthetic events.

Later, a model chain to obtain the hazards' Pathway was set and implemented. The validation of both models in the model chain (SWAN and XBeach) was performed using the St Esteve 2008 event (Sanuy and Jiménez, 2017). Better validations of the model chain could be achieved using more storms to cover a representative range of characteristics for the site.

Regarding receptors and consequences, the locations of receptors have little associated uncertainty. Houses and promenades were derived from accurate land use data available for the site, and the campsite elements were manually located and delimited from available GIS-based tools and raster imagery. Some uncertainty remains, associated with the natural mobility of some campsite elements between seasons. Identification of receptors was static in time and based on assuming the worst case (i.e. campsite elements present at any campsite space allocated to them). A future projection of distribution and number of receptors was not performed.

The damage curves used in the analysis for Houses and Campsite elements (Table 3) were derived from the recommendations by Agència Catalana de l'Aigua (2014) and the FEMA (2001) guidelines; therefore, no specific depth-damage curve derived and calibrated for this specific site was used, which may introduce additional uncertainty to the performed analysis on induced damages. Erosion buffers were selected according to the experience from the side, and aimed to represent the impact on the protective function of the coast. Additional assessments could include the impact on the recreational function related to the loss of beach width.

The CCS based on RCP8.5 SLR had the inherent uncertainties of said projections. The effect of directional changes of incoming storms represents a hypothetical scenario for comparison purposes. Casas-Prat and Sierra (2012) predicted directional changes related to mean sea conditions, but whether these changes will also affect storms is uncertain.

Regarding the DRR measures, it was assumed that protective strategies are completely and efficiently implemented when the storm event occurs. This means that for the FRM, it was assumed that all elements in the area (campsites and houses) implemented flood-proofing measures. However, social and economic conditions influence the percentage of campsite or house owners in the area that take flood-proofing measures, likely reducing this value to below 100%. Further research is needed at the case study site for accurate estimations.

In terms of the setback analysis, we did not consider the background erosion of the area (Jiménez et al., 2017). The measure is valid to cope with storm-induced hazards, but to be efficient in time, setback distances must be increased to include the expected magnitude of decadal shoreline retreat. This also applies to infrastructural measures, as the N+D was assumed to be in place every time a storm reaches the coast. This means that beach nourishment would have to be rebuilt each time after being eroded during a storm event to maintain the 50-m increase in beach width. Moreover, it was assumed that the position and level of the barriers are adapted to the new position of the shoreline along with the predicted SLR.

Despite the limitations, the results obtained mimic the system behaviour under present conditions. For instance, the temporary capability of beach nourishment to protect the site against erosion is well known in the Tordera Delta, where several nourishments have been implemented over the last decade at both sides of the river mouth with the same outcome. The measure was completely washed out after the first incoming storm event. However, this measure should be considered in the DRR comparison, since one of the main needs of the economic activity of the area (campsites) is having a sandy beach available in front.

North of the river mouth (S'Abanell), erosion and overwash problems are the main issue for campsites and the promenade (Jiménez et al., 2011). This is well captured by the tool, which shows a notable increase of these impacts under the SLR. This is similar to the observed increase in damages due to the decadal background erosion of the site, where campsites located in unprotected areas are forced to lose the first line of elements progressively impacted by storms. The coastal promenade has also experienced increased damages over the last decades (Jiménez et al., 2011).

Thus, the primary results summarised in the following and observed as in accordance with known reality, are useful in providing coastal managers with an integrated global picture of the impacts at the site and the best measures to counter them.

The overall results indicate that both sites of the river mouth are likely to double expected flooding impacts after the SLR (CCS1). South of the river, impacts are also likely to double because of a switch in the direction of incoming storms, even without an increase in the MSL (CCS2). Therefore, at that side of the river, the combination of these two factors (CCS3) is likely to triple the expected flooding risk. This is not the case at the north of the Tordera, where the orientation of the coast means that the directional switch does not imply any significant increase on the extension and magnitude of flooding. The erosion hazard is likely to increase under CCS1, and no significant increase is expected for the other two climate change scenarios (CCS2 and CCS3). The expected increase in erosion impacts is larger than for flooding, since the beach accommodation and future MSL mean that receptors are likely to be affected by erosion. Furthermore, the magnitude of the hazard itself is expected to worsen one magnitude in the present situation.

The most efficient DRR against flooding is beach nourishment and dunes, and the best option against erosion is managed retreat. However, each measure has drawbacks from the socio-economic standpoint, which must be assessed in a further step, since the aim of the BN tool is to objectively assess the efficiency of reducing impacts.

5.2 Lido degli Estensi-Spina

Regarding storm characterisation, the events were designed using triangular design storms. Although this practice is common for numerical investigations, especially for erosion issues (e.g. Carley and Cox, 2003; Corbella and Stretch, 2012), the listed assumptions may have introduced a degree of uncertainty in the modelling. This may lead to uncertainties in the simulation of the coastal flood extension and intensity, as well as on the erosion patterns and magnitude. Regarding overall representativeness, it must be highlighted that the forcing events (historical and synthetic) were selected to cover all possible (and realistic) combinations that can affect the area.

The XBeach model setup was affected by simplifications and assumptions as well as the uncertainty related to the input data (i.e. topo-bathymetry merged from different years). A proper calibration was not implemented, but the model was validated against the event in February 2015, evidencing a reasonable fit with observed flood inundation. However, a slight overestimation of the inundated area for the southern part of the Lido di Spina beach was demonstrated. Proper calibration and validation of the model is needed to improve the reliability of the results.

The location of receptors was estimated by cadastral maps from 2013. As an important aspect of risk assessment is the updating of exposed elements, more recent information can improve the results. For the CCS, no increase in exposure was considered, which may lead to underestimating the impacts. For coastal areas, an increase in exposed elements was forecast (IPCC, 2012). This aspect can exacerbate coastal risk at the regional level when compared to increases in local hazard conditions driven by climate change (Sekovski et al., 2015).

Uncertainties related to consequences are linked to the choice of vulnerability functions. The selected flood-damage curve (Scorzini and Frank, 2015) was the most recently developed for river floods in Italy. Although it was developed based on data of damage to residential buildings, it was applied here for coastal floods impacting all types of receptors. This increases the degree of uncertainty of the results, as the expected damages to a concession are likely to be lower than for a residential building for a given water depth. The methodology applied to link erosion patterns and potential damages was set *a priori* using homogeneous thresholds of 0.5 m and a 10-m buffer.

The uncertainties of the CCS definition are related to the reliability of the SLR future projections. Indeed, the RMSE of the predicted RSLR (including subsidence) was 28 cm in the northern Adriatic (the average RMSE for the central Mediterranean was 14 cm) (Vousdoukas et al., 2016). Thus, more detailed and consistent data may lead to more reliable impact projections. Moreover, the CCS was implemented without considering implicitly in the modelling the long-term morphological adaptation of the beach to SLR. However, this aspect can be assessed *a posteriori* through a profile response equilibrium model (Bruun, 1962).

The WD system was implemented modifying the topography in front of beach concessions using the Dune Maker 2.0 tool (Harley, 2014). The accuracy of the representation of this feature strongly depends on the alongshore resolution of the model, as the WD develops in that direction. Moreover, only one type of WD was tested, while more configurations should be investigated in which the geometry of the system is varied. It is important to underline that the efficiency of artificial dunes strictly depends on the beach width. Therefore, as observed by Harley and Ciavola (2013), the dune height and crest width (i.e. the sand volume of the dune) should be designed differently for different coastal stretches, such as the case of Lido degli Estensi-Spina, where the beach characteristics are not uniform. The location of the sand dune with respect to the MSL is another important component that can affect the final results.

The FRM measure was assumed *a priori* as completely effective. However, as its implementation depends on physical and socio-economic factors (e.g. education, economic status, etc.), which can decrease the efficiency of the measure, the assumption leads to overestimating its effect.

Despite the highlighted limitations, the comparative analysis of scenarios is robust and valid. Impacts related to the CUS are reliable in terms of magnitude and comparable with the knowledge of the area (Perini et al., 2016; Trembanis et al., n.d.). Moreover, the dominance of water level characteristics of storms on the impacts of flooding compared to wave characteristics is highlighted in previous works (e.g. Armaroli et al., 2012).

The impacts in the CCS increased compared to the CUS for all tested cases. In addition, when beach accommodation to the SLR was assessed *a posteriori*, the obtained shoreline retreat (Bruun, 1962) is 60–100 m, leading to a significant loss of the protective function of the beach. Thus, including beach accommodation would probably lead to higher erosion and flooding impacts than those previously presented.

As expected, the WD measure is effective in decreasing the impacts of flooding, as previously demonstrated by Harley and Ciavola (2013). Their research focused on two case studies in the Ravenna province, and tested different dune geometries against the impacts of the February 2012 event. That work and others (Bruun, 1983; Wells and McNinch, 1991) highlights the need for appropriate guidelines for dune implementation to limit beach manipulation due to scraping activities. Beach manipulation can lead to undesired changes in slopes (Wells and McNinch, 1991), and consequently in morphodynamics, which can locally increase the impacts of storms. In the case of Lido degli Estensi-Spina, the increase in erosion impacts on a few receptors can be attributed to the relative position between the receptors and discontinuities of the dune, which was designed as a non-continuous morphology. The induced alongshore variability increased localised erosive impacts. This was in contrast to the general decrease of erosion consequences for the majority of receptors, as demonstrated for the WD scenario compared to the configuration without DRR. The effect of the WD on adjacent beaches was not analysed. However, the scraping depths were in the range proposed by Bruun (1983) to avoid effects on adjacent beaches. The interest in FRM was related to the opportunity to merge the measure with the WD system. Indeed, the combination of measures can effectively reduce damage caused by floods.

6 Conclusions

In this paper, a methodological framework for storm-induced coastal risk management purposes developed within the framework of the RISC-KIT EU project was presented and applied in two coastal study sites in the North-Western Mediterranean and Northern Adriatic coasts. The study was is based on the integration of the SPRC concept model in a BN. This was fed with a large number of numerical simulations obtained through a model chain composed of process-oriented model chain models able to reproduce simulate multiple storm-induced hazards at the receptor scale. The BN integrates impact results that individually account for all receptors in the hinterland. Once developed, the BN can The tool can be regularly updated with additional simulations and further extended with new scenarios.

The BN has been fed with uniform distributions ofThe choice and discretisation of storms covering the range of representative conditions storm variables to perform the analysis covered all possible and realistic combinations at both study sites. This permitted to assess the performance of different risk reduction strategies to individual hazards and under different climate scenarios.~~The entire range of characteristics of forcing events was appropriately represented.~~

In spite of not statistically mimicking the maritime climate, ~~At both study sites, the implemented model chains successfully predicted the coastal response to storm events. Target hazards were suitably captured though the process-based models, which simultaneously assessed erosion and inundation.~~

~~A BN was used to integrated results, calculated at the receptor scale, from a large number of simulations to produce a robust comparative assessment. It was successful in detecting significant changes on expected impacts. Therefore, even with the inherent uncertainties and limitations, the BN approach allows realistic scenario testing and comparisons between DRRs.~~

~~Many types of results can be extracted from the BN tool once fed with data that are easy to interpret and quantitative (and therefore comparable). As expected, this work confirmed the potential of the BN as a probabilistic data assimilation approach.~~

~~At both study sites, ~~the approach demonstrated impact responses in the current situation in accordance with existing knowledge ~~on the~~at both sites. Tordera Delta, which is characterised by quick and intense erosive responses to storms, showed greater impacts to erosion than Lido degli Estensi-Spina and they were essentially concentrated in infrastructures located just behind the beach.~~ Inundation and erosion impacts are likely to increase in all assessed future projections at both study sites~~. As expected, the flooding impact in the current situation ~~and projected increase in future scenarios ~~is higher for receptors located closest to the shoreline or at the lowest elevation areas ~~most low-lying areas ~~of the hinterland (i.e. concessions at Lido di Spina and campsites at Malgrat).

The estimated risk significantly increases for the climate change scenario. Regarding the impacts of future projected erosion, the obtained increase at the Tordera Delta was significantly higher than in the Lido degli Estensi-Spina, because of the morphological accommodation response to the projected MSL. This highlights the importance of including morphological adaptation to the SLR in impact and risk assessment studies.

From the tested risk reduction strategies, ~~The DRR assessment highlighted as effective ~~the construction of artificial dunes was identified as very effective for inundation at both study sites, whereas its efficiency for managing erosion was lower. ~~as protection against inundation at both study sites, even when compared to other measures such as managed retreats or flood resilience measures applied to all receptors. However, the dune was less effective and sometimes ineffective against erosion at both study sites. ~~On the other hand, and a~~A~~s expected, setback definition and managed retreat ~~and derived from results for the Tordera Delta, dune performance against flooding improved when tested along with beach nourishment. However, beach nourishment did not improve dune performance against erosion. Managed retreat ~~seems to be the best option to tackle the impacts of erosion.

This conclusion is valid provided the coastal morphology before storm impacts is well represented by the used morphology. If the assessment has to be valid for future decisions, expected changes in coastal morphology need to be accounted for.

Finally, although the developed framework has proven to be efficient to analyze storm-induced risks and strategies to cope with them, a series of elements to be addressed to further improve it and to extend its applicability have been identified and discussed. In this sense, the BN is a versatile tool to make robust comparisons across different conditions and to incorporate different sources of uncertainty

The approach can be further improved by addressing the limitations discussed in Section 5, including data and methodological improvements that may increase computational efforts.

In conclusion, coastal management can be significantly improved by methodologies based on the integration of large amounts of data, stochastically condensed so that multiple scenarios can be easily compared. Uncertainties due to data quality, numerical approximation, simplifications, and assumptions will always be present. However, the assimilation of results and their uncertainties though a BN provides robust comparison across different conditions. Therefore, the observed variations of impacts, when significant, will help decision-makers select between strategic alternatives of DRRs.

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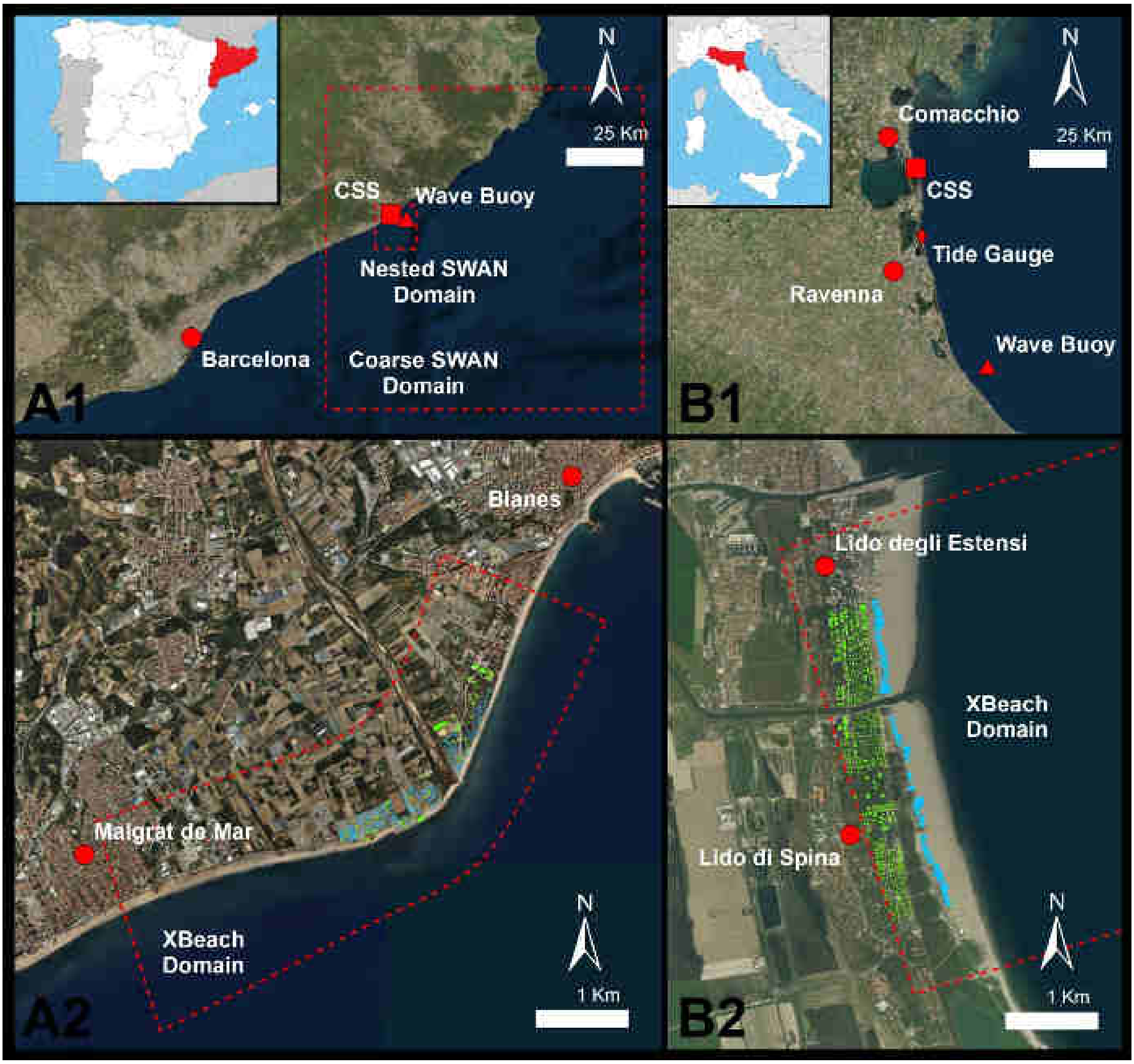


Figure 1: Regional and local contexts: A1) the central-northern Catalan coast; B1) Emilia-Romagna coast; A2) local hotspots of Tordera Delta; B2) local hotspots of Lido degli Estensi-Spina (2b). The main locations (red dots), wave buoys (red triangles), tide gauge (red diamond), and the ~~CSS~~ case study sites (red squares). The domains of the large-scale and local models (dashed red lines) are highlighted for each box.

Figure 2: Impacts on the Tordera Delta. Destruction of a road at Malgrat (A); overwash at campsites north of the river mouth (B); destruction of the promenade north of the river mouth (C); beach erosion, and damage to utilities and buildings at Malgrat (D and E).

Figure 3: Impacts of the event in February 2015 on the Lido degli Estensi-Spina case study area. Impacts of erosion and flooding on concessions at Lido di Spina south (A, B) and Lido degli Estensi (C); sandy scarp due to the erosion of the dune in the south of Lido di Spina (D); eroded Winter Dune in Porto Garibaldi (E); damages to the Porto Canale front at the Lido degli Estensi (F).

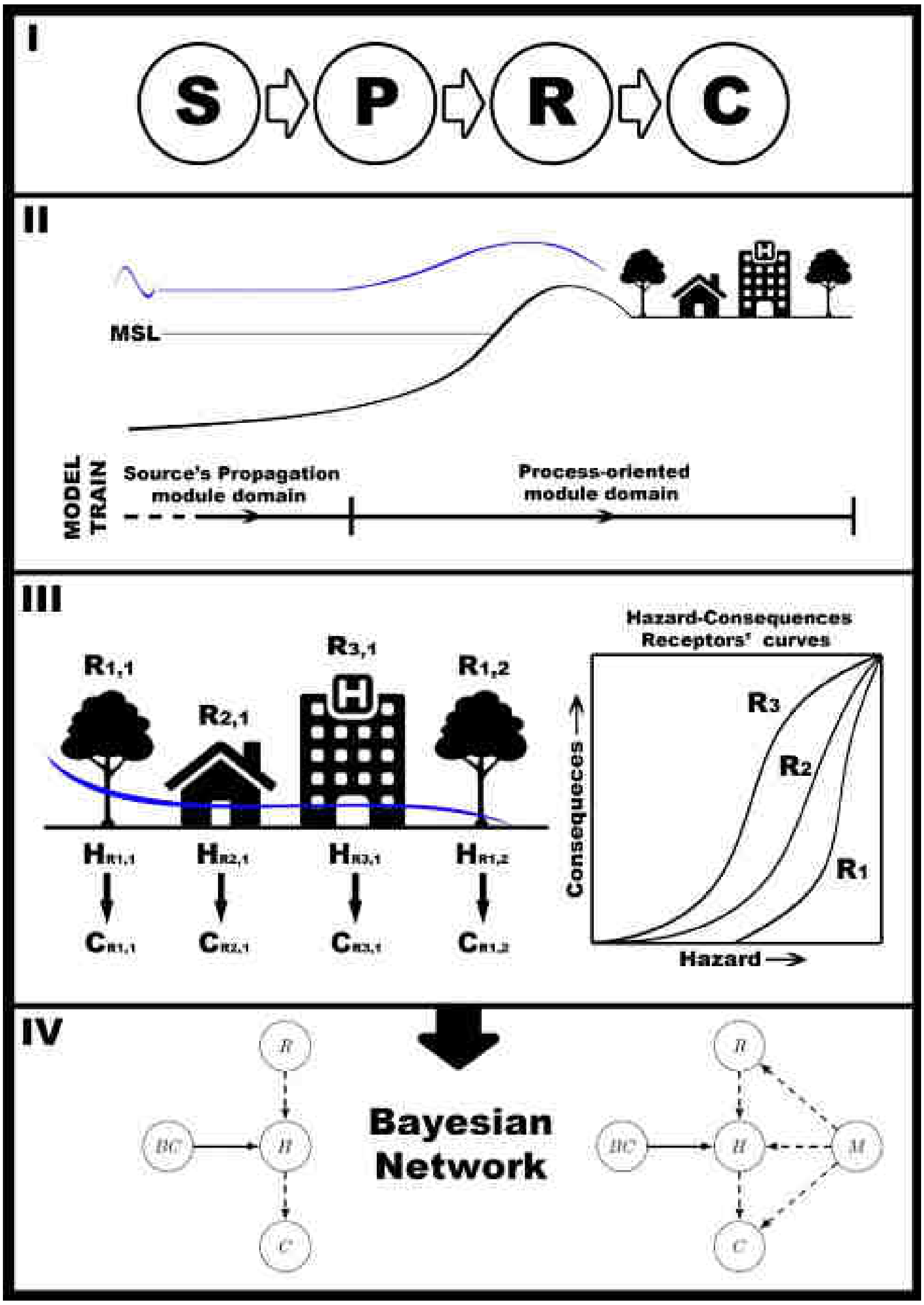


Figure 4: General methodology. (I) The SPRC conceptual framework is implemented through (II) a model chain, which consists of a propagation module of the source (S) and a process-oriented module for the coastal area reproducing the pathway (P). Then, (III) the consequences (C) are calculated based on the computed hazards (H) at the receptor (R) scale by using vulnerability relations (i.e. hazard-consequences functions). In the last step (IV), all variables including source boundary conditions (BC) are fitted in a BN, adding impacts after the implementation of measures (M).

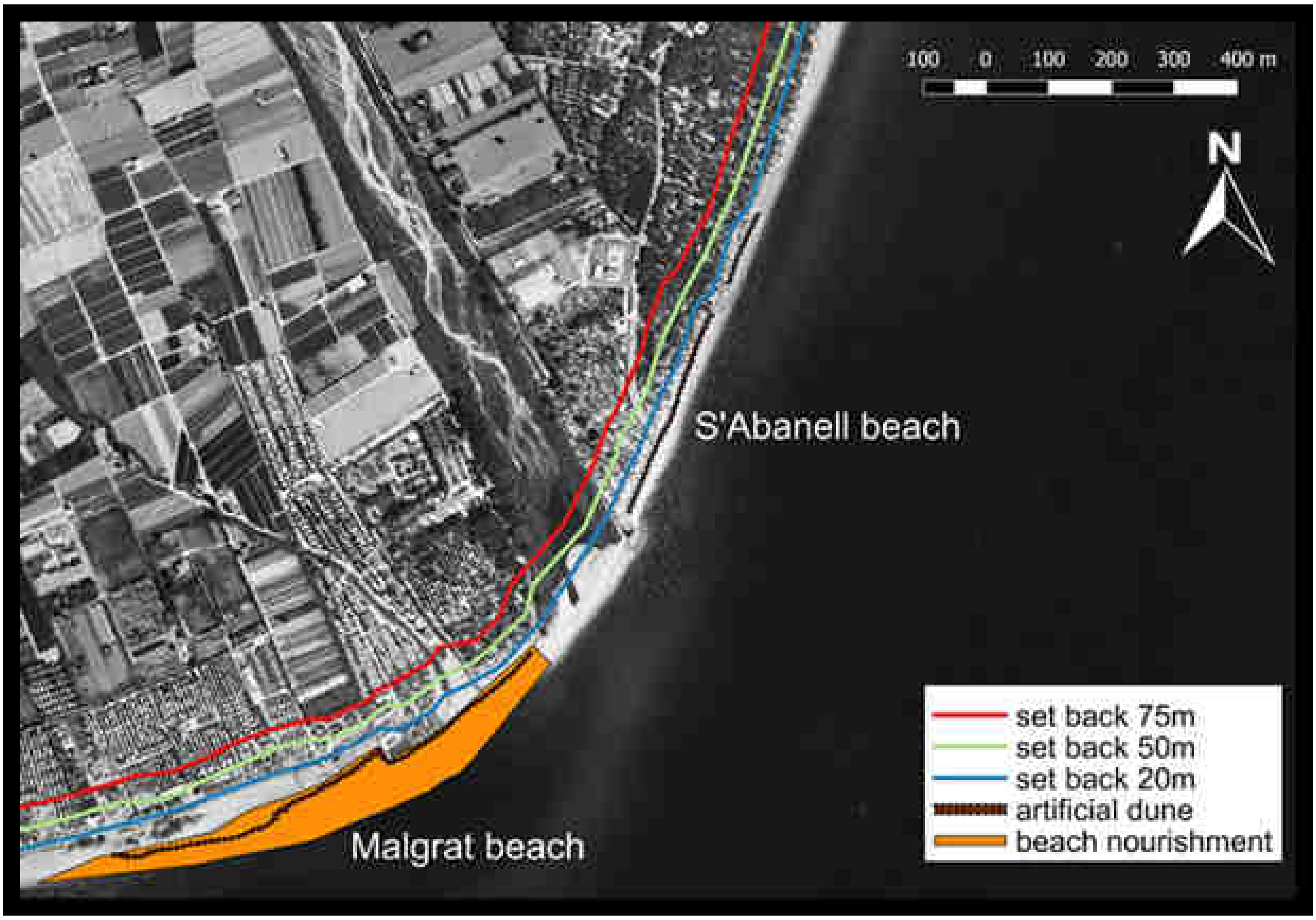


Figure 5: ~~DRR~~ Disaster risk reduction measures at Tordera Delta. ~~Coastal~~ Receptor Ssetbacks (20, 50, and 75 m) and ~~Infrastructural Defence~~Nourishment + Dune (beach nourishment at Malgrat beach + artificial dune at S'Abanell and Malgrat beaches).

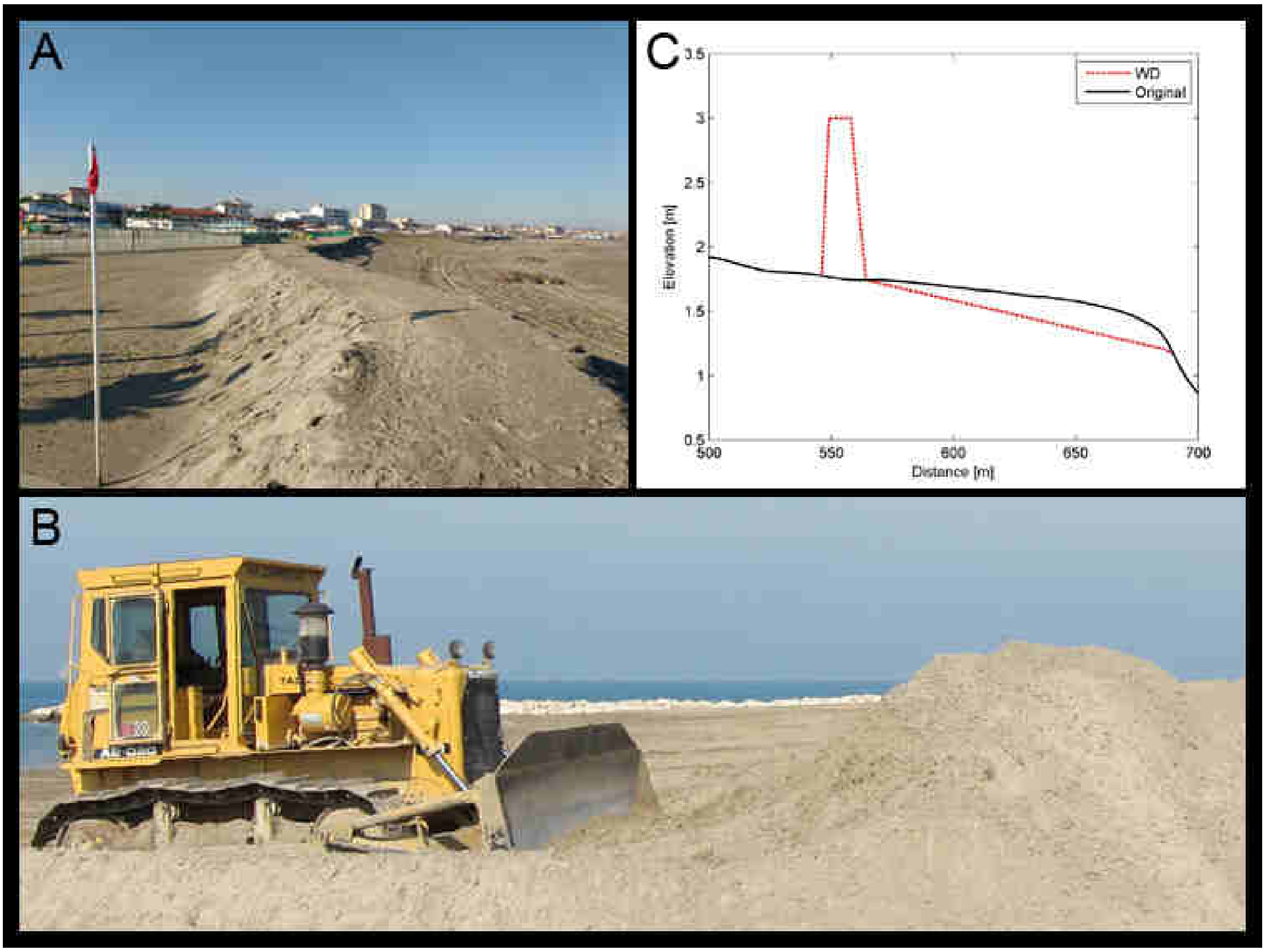


Figure 6: Artificial winter dunes in Emilia-Romagna: A) Winter dune in Porto Garibaldi (Comacchio, Italy); B) Building of a winter dune by beach scraping at Lido di Dante (Ravenna, Italy) (Harley, 2014); C) Representative model profiles at Lido di Spina north (original: black solid line; with winter dune DRR: red dashed line).

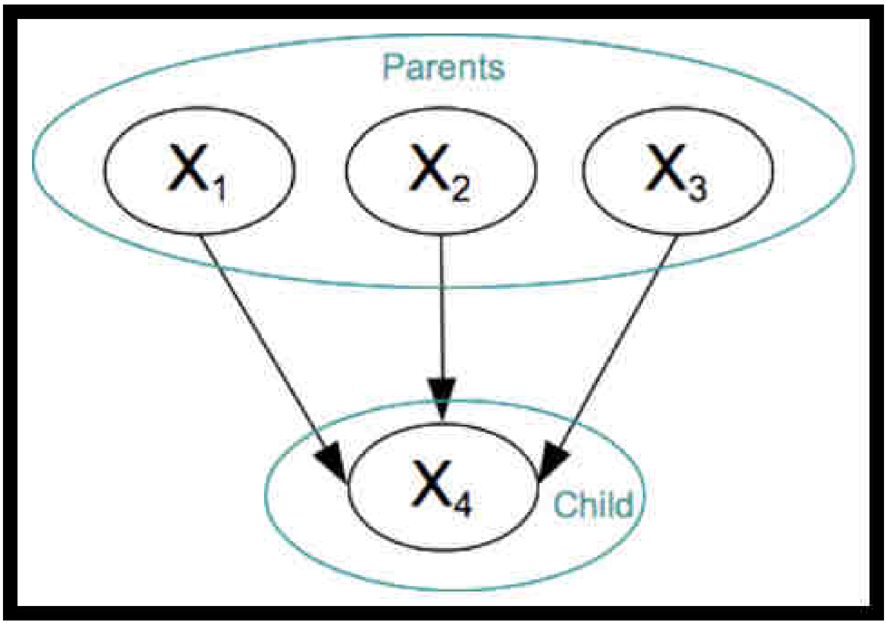


Figure 7: BN graph with four nodes.

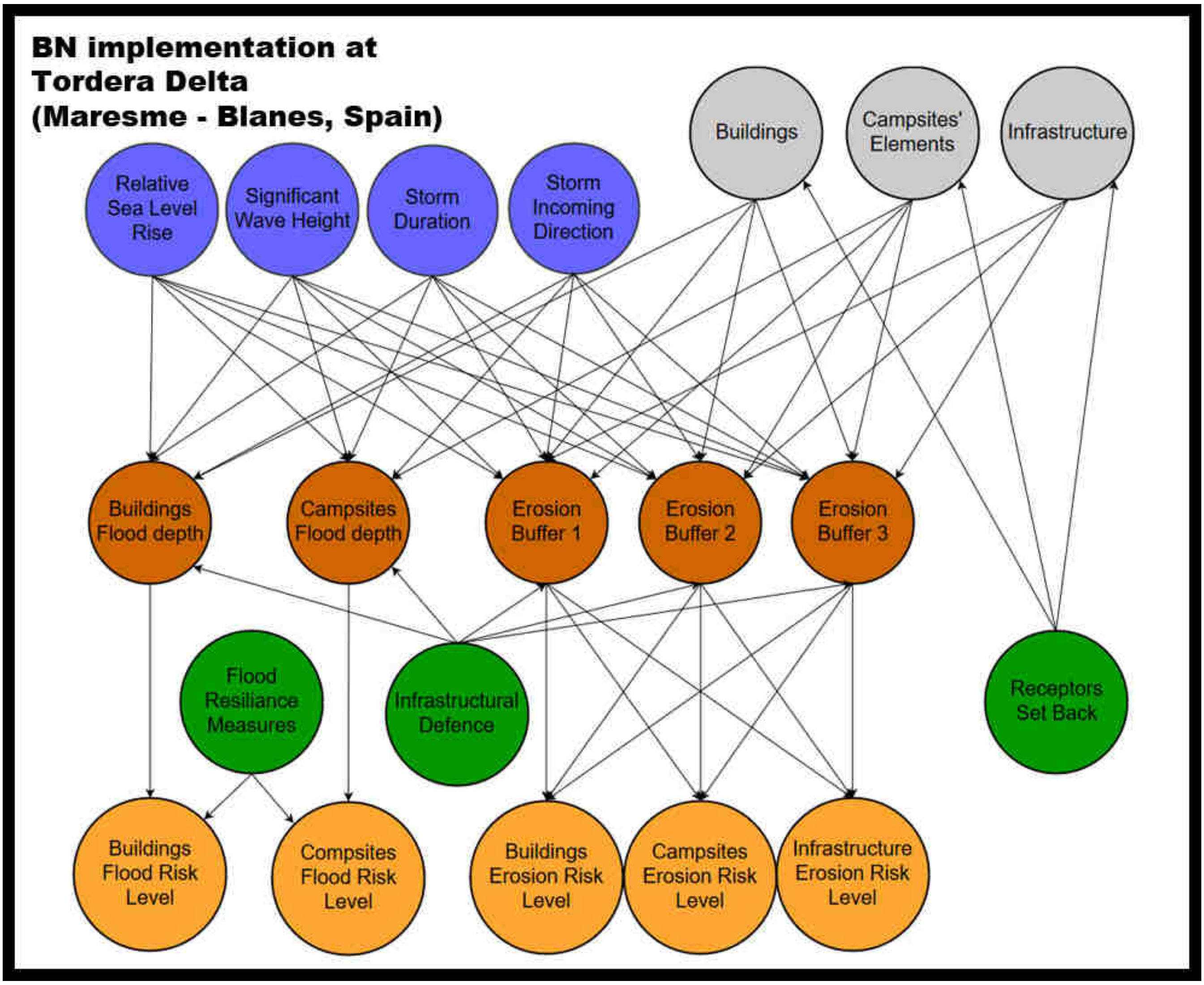


Figure 1: Bayesian Network scheme for the Tordera Delta site.

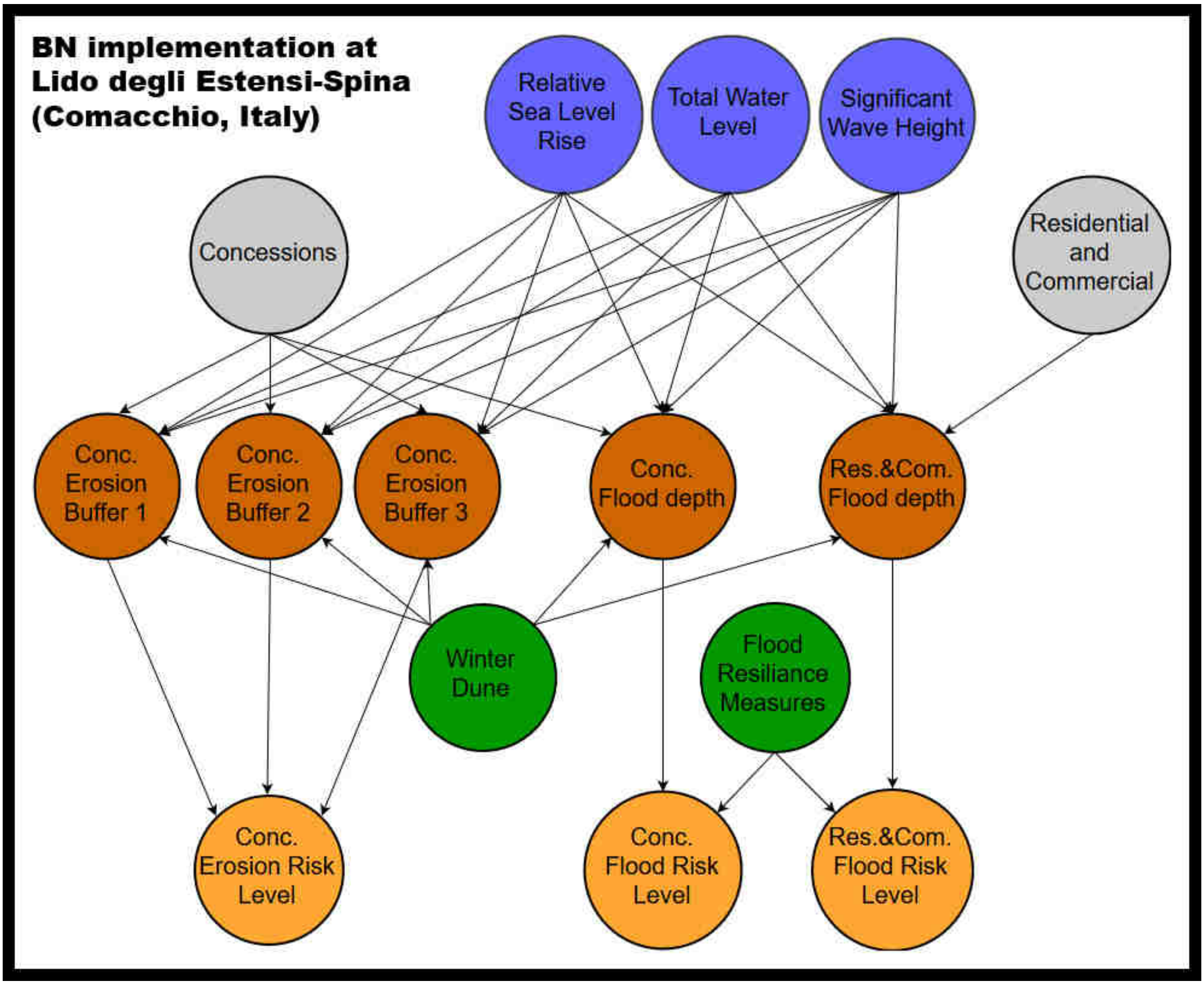


Figure 2: Bayesian Network scheme for the Lido degli Estensi-Spina site.

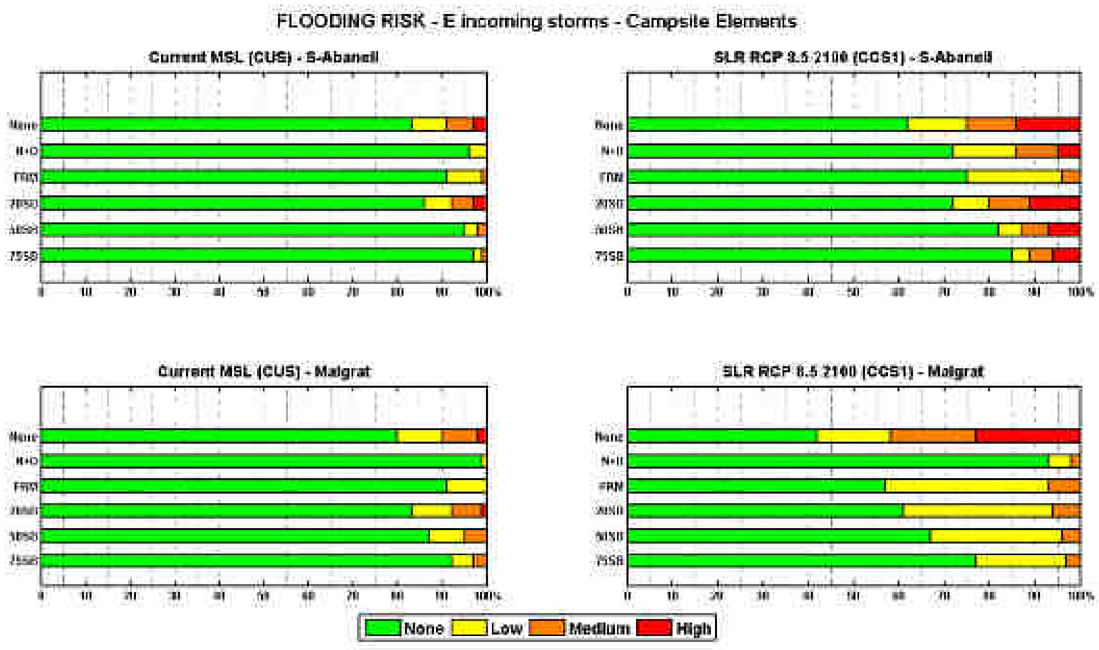


Figure 10: Distribution of campsite elements at every level of flooding risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a ~~DRR~~ risk reduction configuration ('None': no ~~DRR~~ measure implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).

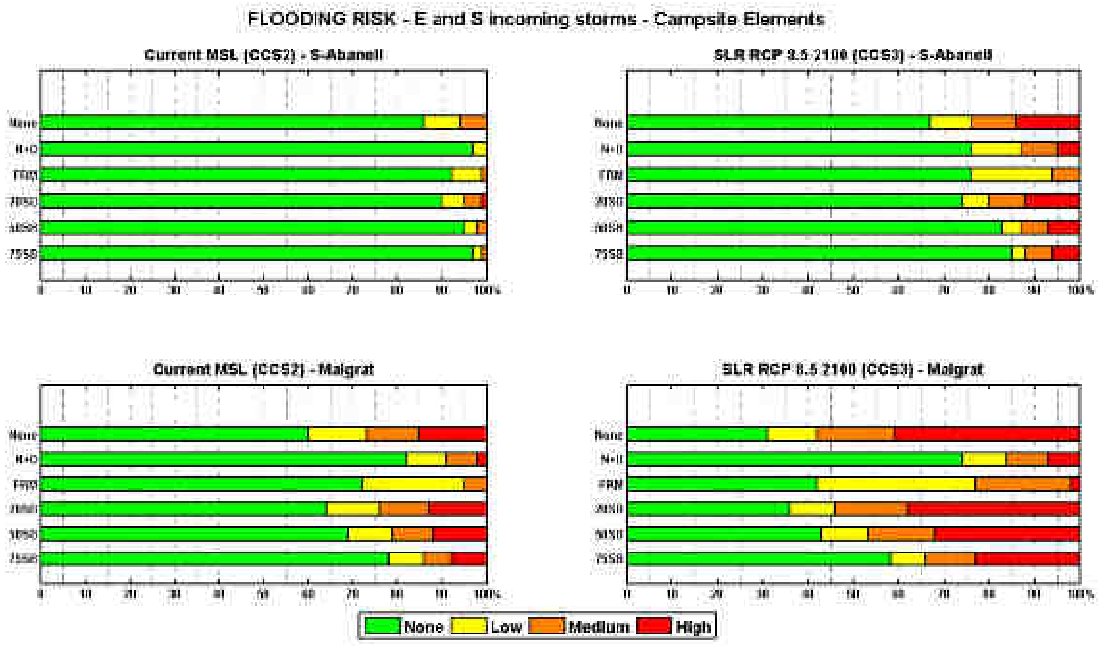


Figure 11: Distribution of campsite elements at every level of flooding risk. Top-left: climate change scenario 2 (50-50% east-south storms) at S'Abanell; Top-right: climate change scenario 3 (50-50% of east-south storms + SLR) at S'Abanell; Bottom-left: climate change scenario 2 (50-50% east-south storms) at Malgrat; Bottom-right: climate change scenario 3 (50-50% of east-south storms + SLR) at Malgrat. Each bar in a panel represents a ~~DRR~~ risk reduction configuration ('None': no ~~DRR~~ measure implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).

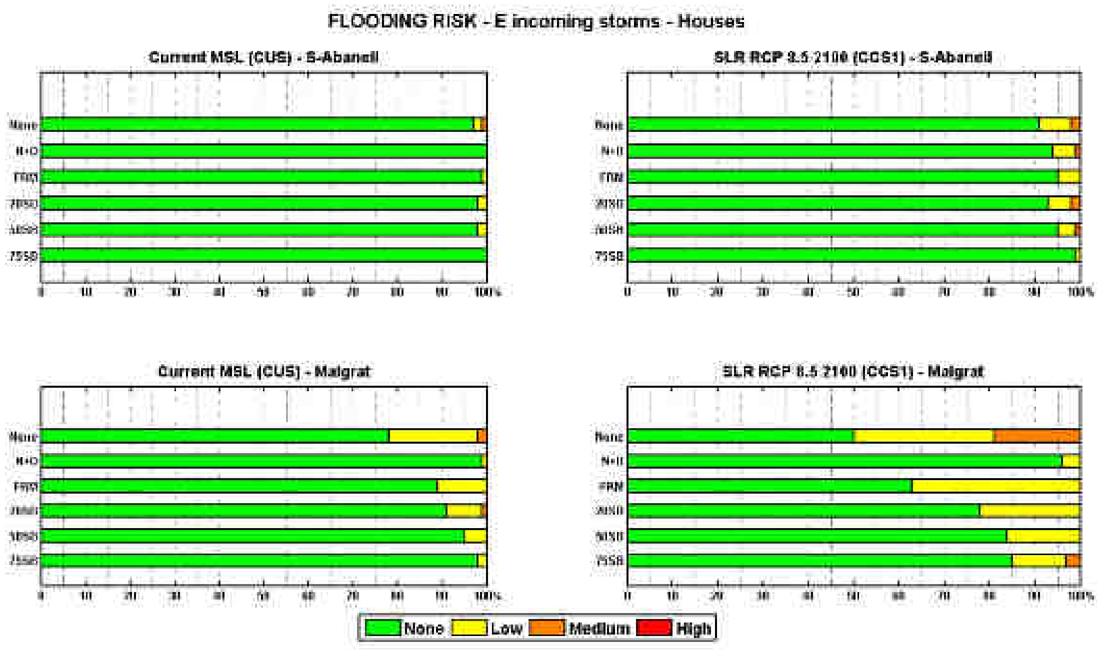


Figure 12: Distribution of houses at every level of flooding risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a DRR configuration ('None': no DRR implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).

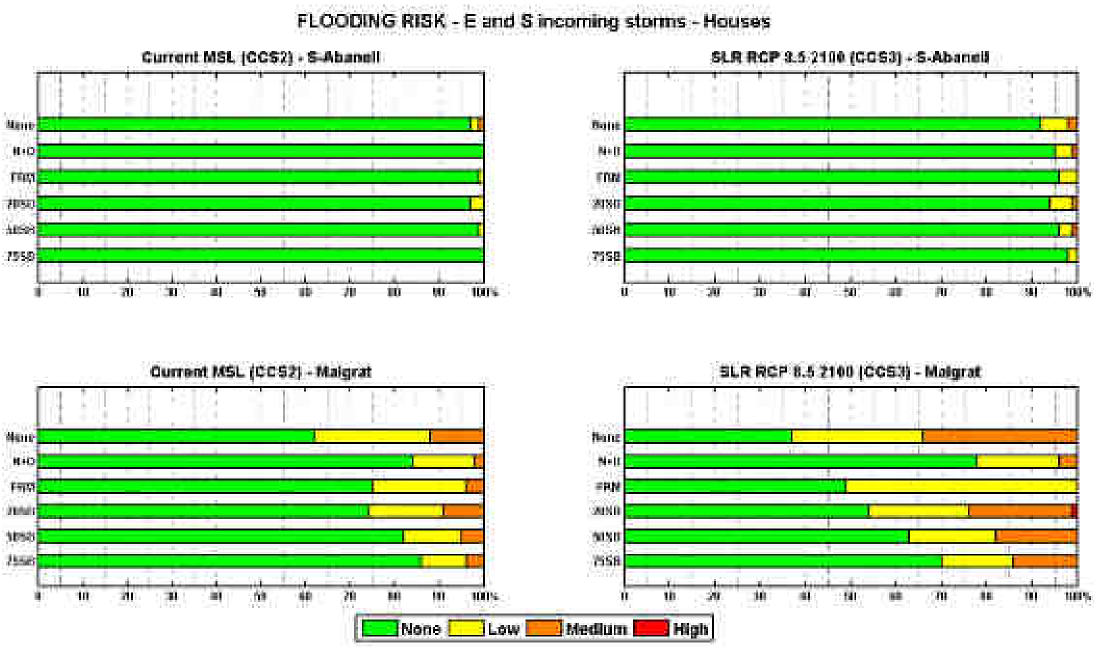
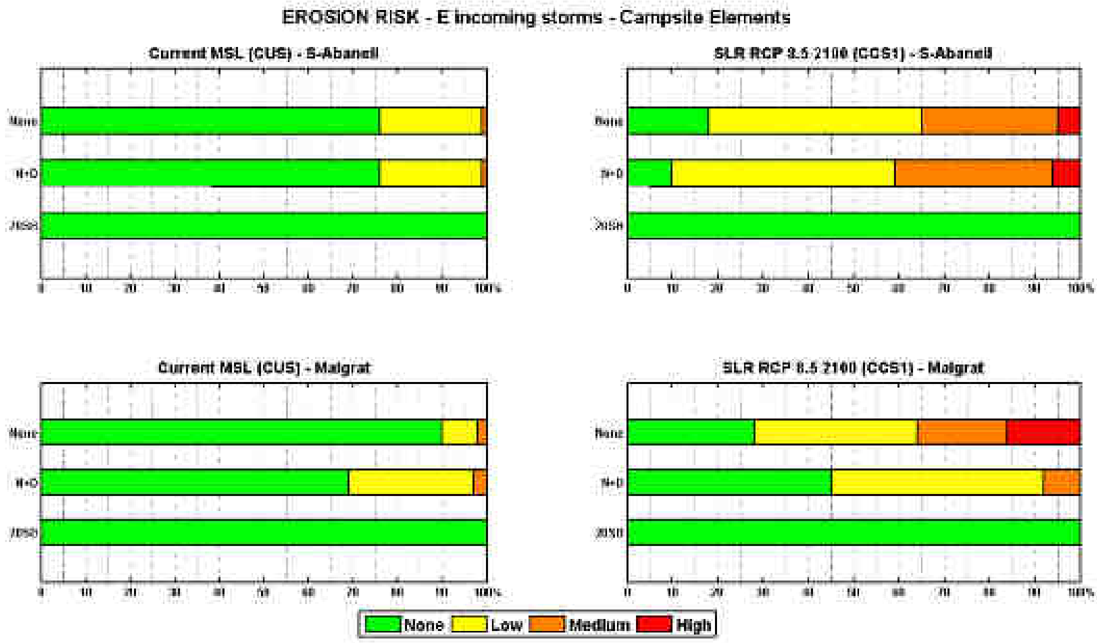


Figure 13: Distribution of houses at every level of flooding risk. Top-left: climate change scenario 2 (50-50% east-south storms) at S'Abanell; Top-right: climate change scenario 3 (50-50% of east-south storms + SLR) at S'Abanell; Bottom-left: climate change scenario 2 (50-50% east-south storms) at Malgrat; Bottom-right: climate change scenario 3 (50-50% of east-south storms + SLR) at Malgrat. Each bar in a panel represents a DRR configuration ('None': no DRR implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).



~~**Figure 14: Distribution of campsite elements at every level erosion risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a DRR configuration ('None': no DRR implemented; 'N+D': Nourishment and Dune; 'FRM': Flood Resilience Measures; '20SB, 50SB, and 75SB': 20, 50, and 75 m setbacks, respectively).**~~

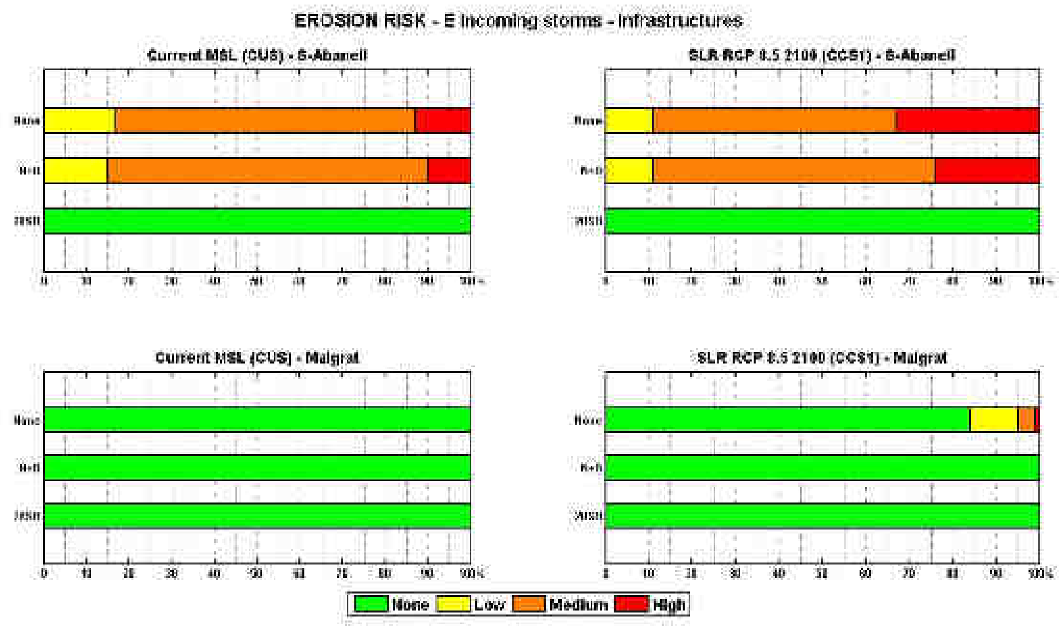


Figure 125: Distribution of Infrastructures at every level erosion risk. Top-left: current scenario at S'Abanell; Top-right: climate change scenario 1 (SLR) at S'Abanell; Bottom-left: current scenario at Malgrat; Bottom-right: climate change scenario 1 (SLR) at Malgrat. Each bar in a panel represents a DRR risk reduction configuration- ('"None'": no DRR measure implemented; '"N+D'": Nourishment and Dune; '"FRM'": Flood Resilience Measures; '"20SB, 50SB, and 75SB'": 20 , 50, and 75 m setbacks, respectively).

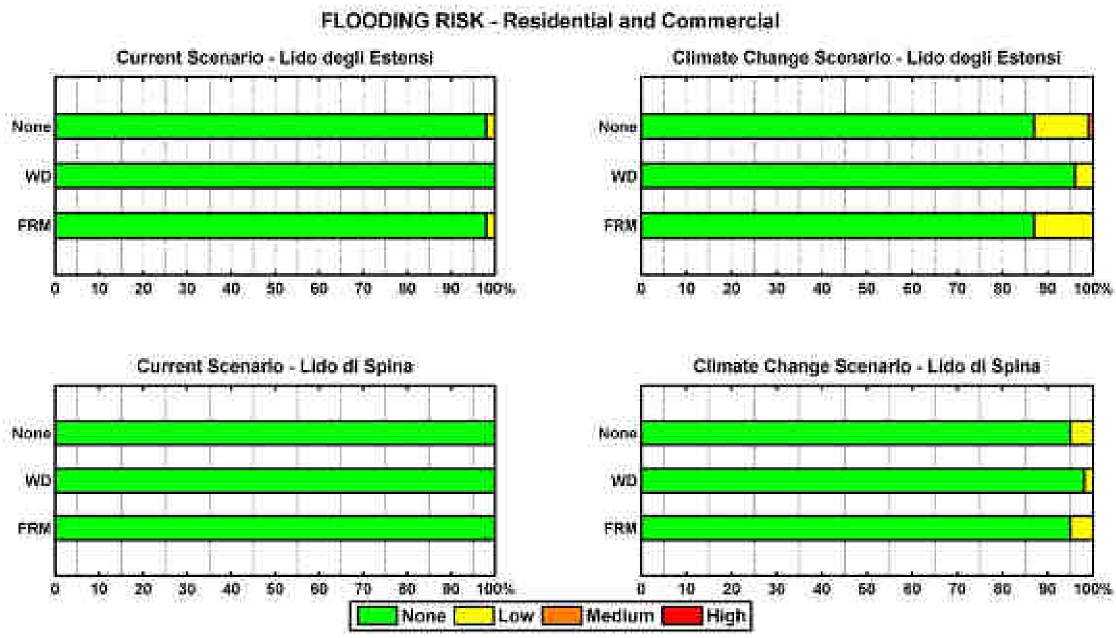


Figure 16: Distribution of residential and commercial buildings for every level of flooding risk. Top left: current scenario at Lido degli Estensi; Top right: climate change scenario at Lido degli Estensi; Bottom left: current scenario at Lido di Spina; Bottom right: climate change scenario at Lido di Spina. Each bar in a panel represents a DRR configuration ('None': no DRR implemented; 'WD': Winter Dune; 'FRM': Flood Resilience Measures).

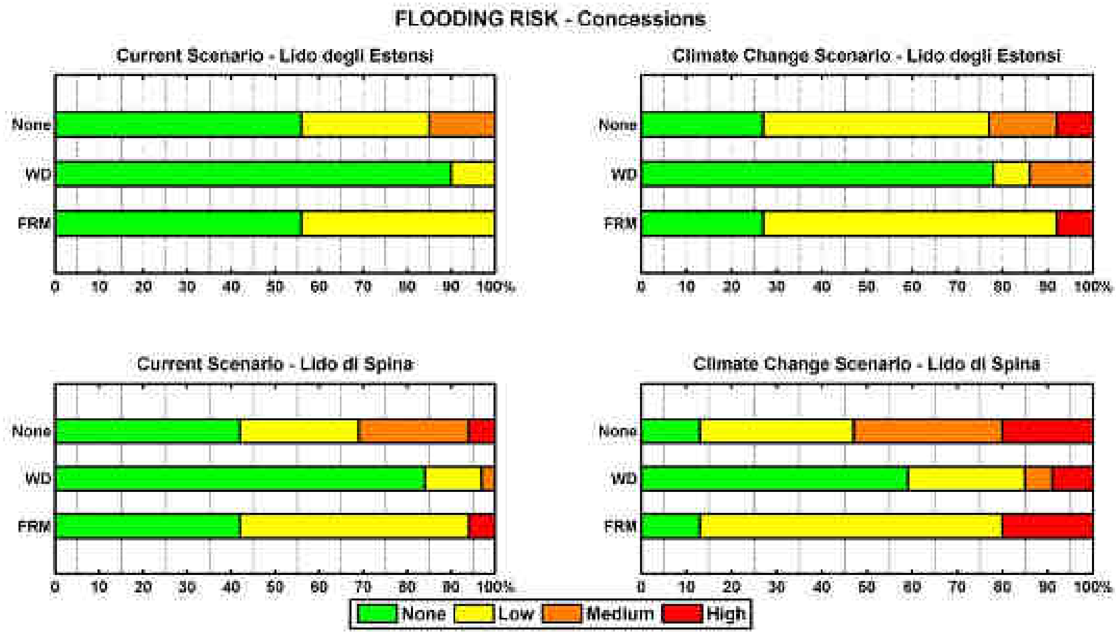


Figure 137: Distribution of concessions for every level of flooding risk. Top left: current scenario at Lido degli Estensi; Top right: climate change scenario at Lido degli Estensi; Bottom left: current scenario at Lido di Spina; Bottom right: climate change scenario at Lido di Spina. Each bar in a panel represents a DRR risk reduction configuration ('None': no measure DRR implemented; 'WD': Winter Dune; 'FRM': Flood Resilience Measures).

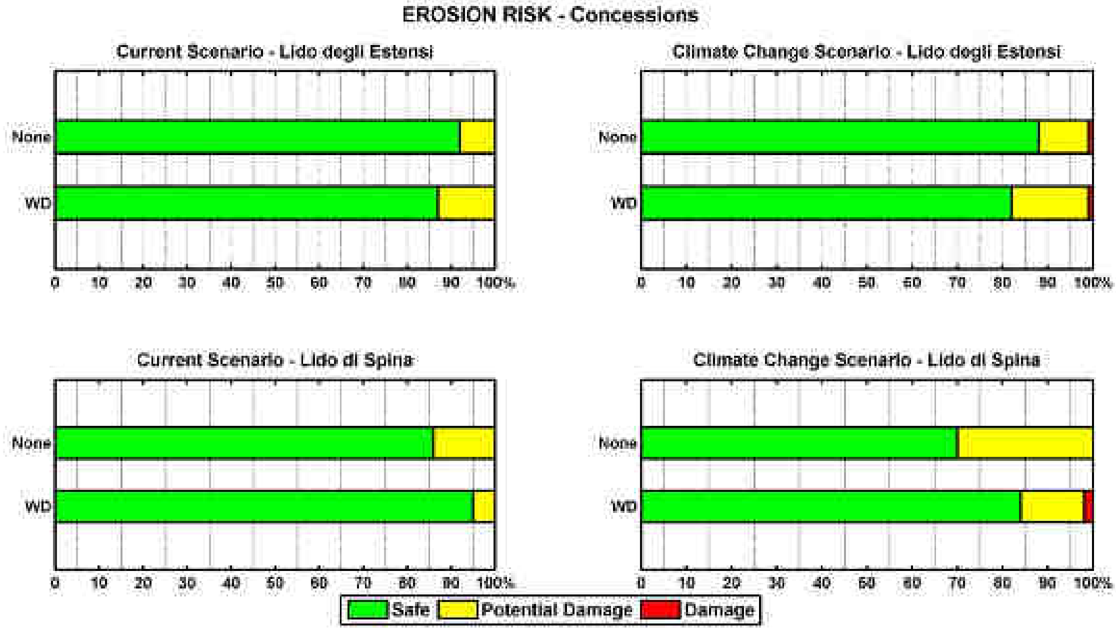


Figure 148: Distribution of concessions for every level of erosion risk. Top left: current scenario at Lido degli Estensi; Top right: climate change scenario at Lido degli Estensi; Bottom left: current scenario at Lido di Spina; Bottom right: climate change scenario at Lido di Spina. Each bar in a panel represents a DRR risk reduction configuration ('None': no DRR measure implemented; 'WD': Winter Dune; 'FRM': Flood Resilience Measures).

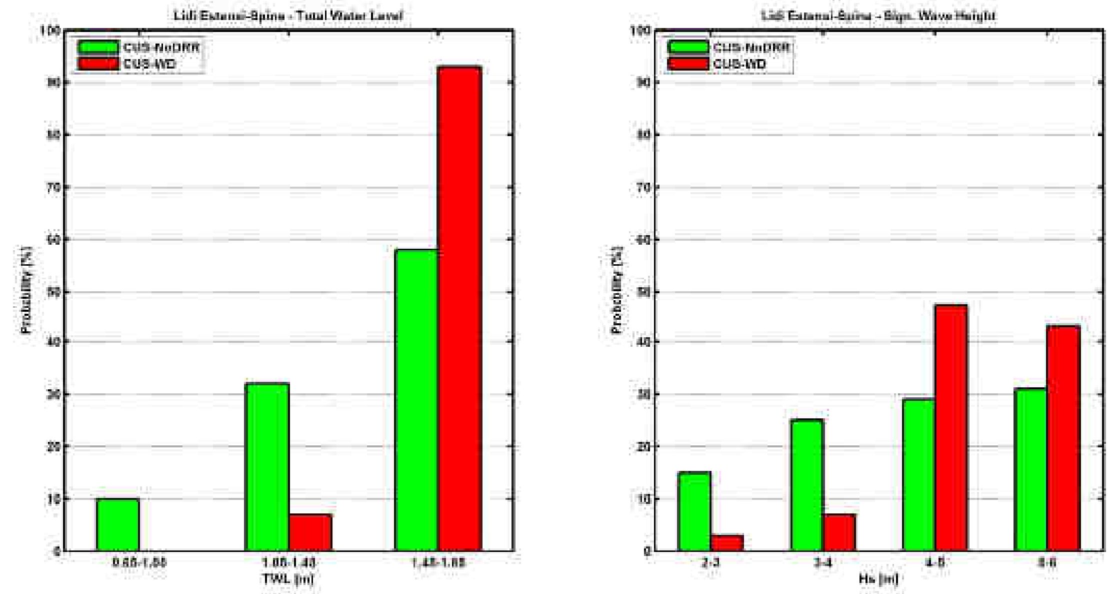


Figure 1~~9~~5: Distribution of boundary conditions (TWL on the left and Hs on the right) ~~that generate~~for constrained uniform flood damages in the current scenario for Lido degli Estensi-Spina. The configuration without ~~DRR~~ measure (green bars) and for the implementation of the ~~WD~~ Winter Dune ~~DRR~~ (red bars) were compared.

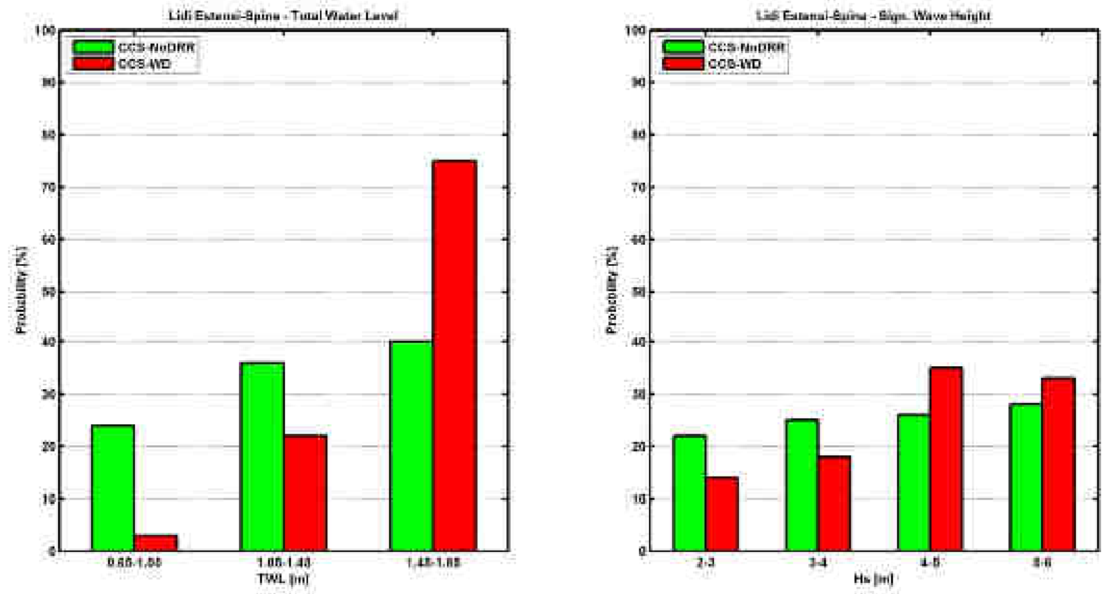


Figure 16~~20~~: Distribution of boundary conditions (TWL on the left and Hs on the right) ~~that generate~~for constrained uniform flood damages in the climate change scenario for Lido degli Estensi-Spina. The configuration without ~~DRR~~ measure (green bars) and under the implementation of the ~~WD DRR~~Winter Dune (red bars) were compared.

Table <u>1</u>~~1~~: Source characterization. Variable discretization applied at the study sites.<u> NC denotes a variable not considered in a study case, and therefore not divided in ranges.</u>

	Hs ~~ranges~~ (m)	Storm Duration (h)	Incoming direction (°N)	<u>TWL(tide+surge)</u> ~~Water level~~ (m)	<u>Mean Sea Level (MSL)</u>
TORDERA DELTA	2 to 3 3 to 4 4 to 5	6 to 30 30-65	30-135 (E) 135-220 (S)	0 to 0.6 m ~~Current + SLR~~<u>NC</u>	<u>Current</u> <u>Current +0.73 m</u> <u>Morph. response included</u>
LIDO DEGLI ESTENSI-SPINA	2 to 3 3 to 4 4 to 5 5 to 6	~~6~~ <u>12</u> – 68 <u>NC</u>	60 to ~~90~~<u>135</u> <u>NC</u>	0.65 to 1.05 1.05 to 1.45 1.45 to 1.85 ~~Current + SLR~~	<u>Current</u> <u>Current+0.30 m</u> <u>No morph. response</u>

Table 2: Distribution of receptors at the Tordera Delta study site.

Area	No. of Houses	No. of Campsite Elements
Area 1 (0 to 20 m *Malgrat de Mar*)	16	45
Area 2 (20 to 50 m *Malgrat de Mar*)	10	71
Area 3 (50 to 75 m *Malgrat de Mar*)	8	169
Area 4 (> 75 m *Malgrat de Mar*)	46	509
Area 5 (0 to 20 m *Blanes*)	1	95
Area 6 (20 to 50 m *Blanes*)	4	156
Area 7 (50 to 75 m *Blanes*)	7	72
Area 8 (> 75 m *Blanes*)	51	189
Total	143	1306

Table 3: Vulnerability relations for houses and campsite elements at the Tordera Delta study site with and without Flood Resilience Measures (FRM)~~**Table 3: Vulnerability relations for houses and campsite elements at the Tordera Delta study site with and without DRR measures (FRM).**~~.

Water depth at the receptor (m)	Relative Damage (%)			
	Houses	Campsites	Houses - FRM	Campsites - FRM
0	0	0	0	0
0-0.3	18.3	50	0	0
0.3-0.6	26.5	71	18.3	50
0.6-0.9	33.2	82	18.3	50
0.9-1.5	44.7	89	26.5	71
1.5-2.1	54.1	91	33.2	82
2.1-3.0	64.5	100	44.7	89
3.0-4.0	71.2	100	54.1	91
4.0-5.0	75	100	64.5	100

Table 34: Distribution of the receptors at Lido degli Estensi and Lido di Spina.

Area	Residential and Commercial Buildings	Concessions
Lido degli Estensi - Seafront	26	16
Lido di Spina - Seafront	47	28

Table 5: Vulnerability relation for flooding adopted for the receptors at Lido degli Estensi-Spina without (A) and with ~~with DRR measures~~Flood Resilience Measures (B).

Flood Depth [m]	Flood Relative Damage Factor [-]	
	A - adapted from Scorzini and Frank (2015)	B - modified considering the FRM
0	0	0
<0.3	<0.1	<0.1
0.3 - 0.7	0.1 - 0.2	<0.1
0.7 - 1.1	0.2 - 0.3	0.2 - 0.3
>1.1	>0.3	>0.3