

Author's response

We want to thank the reviewers for giving us the opportunity to submit an improved draft of the manuscript titled *Cost-benefit analysis of coastal flood defence measures in the North Adriatic Sea*. We appreciate the time and effort that you have dedicated to providing your valuable feedback on the manuscript. We have been able to incorporate changes to reflect most of the suggestions provided. We have enabled the track changes within the manuscript. The spelling and wording have been extensively revised following criteria of clarity, coherence and brevity.

Following is a point-by-point response to the reviewers' comments and suggestions.

Reviewer #1

General comment: I would clearly specify that Authors are referring to residential (or mixed) buildings only. It is only sometimes mentioned, while the scope of the manuscript appears to be a general cost-benefit analysis that includes other sectors too (infrastructures, industrial and commercial buildings, population, heritage and natural sites) and maybe also indirect damages. I would at least specify it in the introduction and remember it in the conclusions. Consider also to mention it also in the titles of paragraphs 3.7 and 4.2 and in the graphs' titles.

- Thank you for pointing this out, we clarified that only residential buildings are accounted in both the introduction and the conclusions, and specified that residential buildings represent 93% of total area.

Introduction: I suggest adding a paragraph about the situation in Italy, in order to introduce and justify the study area.

- We agree with your suggestion. We amended ch.2 adding more context and references regarding the situation of the Italian coast and the specific case study location.

Ch. 2 and Sec. 3.1: I would add some references, although the reader can find most of them in the flowing sections, but at a first read, they seem to be missing (e.g., about subsidence in the Padan plain at P2 L78-79 and VLM rates at P3 L102).

- Agreed, the same key references were added in both sections.

P3 L85-86: it is not clear to me how the sea level events' increasing is related to the socio-economic development of the coast. Please clarify.

- Thanks for pointing this out, the section has been amended and extended. The sentence was corrected:

The number of ESL events reported to cause impacts along the Emilia-Romagna coast shows a steady increase since the second half of the past century (Perini et al. 2011), which is in part explained by to the socio-economic development of the coast exposing increasing asset to flood risk.

P3 L93: please provide some examples (years?) of coastal storms resulting in flooding of buildings and activities in the study area.

- Thank you for your valuable comment, we agree that more examples of flood impacts are needed to give better context, accordingly we extended ch.2 adding details about 3 recent dates, and some impact description from the latest (more severe) one.

P8 L245-247: I think the verb is missing, please correct.

- Thank you, we have fixed the sentence by adding the missing verb.

P8 L249: what about infrastructures and natural sites (mentioned on P3 L240)?

- We revised the explanation in ch 2: "The curve covers only residential and mixed-residential buildings, the area of which represents about 93% of total exposed footprints; other types (e.g. harbour infrastructures, industrial, commercial, historical monuments and natural sites) are excluded from risk computation."

P8 L 259-261: the statement about the validation of the depth-damage function on Italian empirical data is a repetition.

- Thanks, the sentence has been corrected.

P9 L279: please provide a reference or a justification to the 6 M€.

- Thank you for this important comment, the section about costs has been extended with all the justifications from official referenced sources in par. 3.8; numbers were also updated in the analysis.

P9 L 292: "costs" instead of "cots".

- Thanks, fixed.

Figures 8-9 (left): I would suggest plotting the defended scenarios too, so that the reader can immediately see the differences and be introduced to the right histograms.

- We agree on your suggestion, the two scenarios are plotted together in figure 8 and 9; however, it might be a bit difficult to read for Cesenatico, due to curves overlapping.

P14 L388: is the velocity as output needed? It is not used in the analysis...

- Thanks, you are correct, velocity is not used in our risk assessment framework. Accordingly, we removed it from the list of model outputs for the analysis.

Appendix A is never cited in the text. Please correct.

- Thank you, it is now mentioned in the section about discount rate.

Reviewer #2

Specific Comments

Line 52: DRR project abbreviation is not defined. Please define for the readers' convenience.

- Thank you for pointing this out, full notation was added.

Line 68: Similarly, please define "ISTAT". If this is a reference, please include in the reference list.

- Agreed, ISTAT added as a reference.

Line 78: The authors suggest "... In addition to that, all the coastal profile of the Padan plain shows relatively fast subsiding rates, partially due to natural phenomena, but in large part linked to human activities." I believe this is land subsidence caused by landwater drainage. Please be more specific.

- That is true, and it is explained with more details in following par. 3.2:

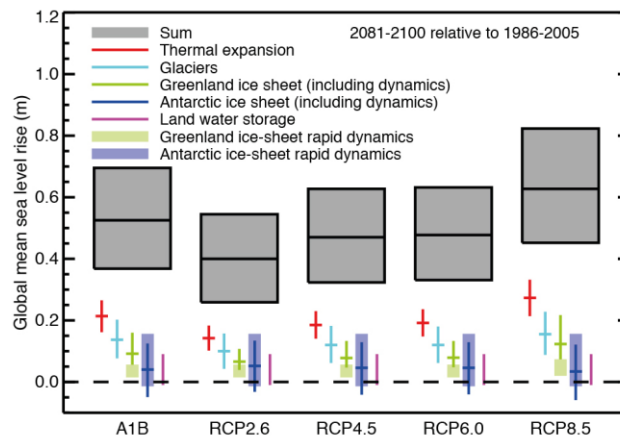
Observed subsidence is about one order of magnitude faster where the aquifer system has been extensively exploited for agricultural, industrial and civil use since the post-war industrial boom. From the 1970s, however, with the halt of groundwater withdrawals, anthropogenic subsidence has been strongly reduced or stopped, but many of the induced effects still remain.

Line 85-87: The authors state that ESL events are increasing due to socio-economic development of the coast? How? The socio-economic development could only affect the "impacts" of the ESLs, not ESLs as hazard levels. Please correct this sentence.

- Thank you for your most valuable comment, we agree that this was not clear, and the sentence has been amended.

Line150: The authors used RCP4.5 for the future projections of SLR. It would be interesting to see what happens with RCP8.5.

- Thank you for this suggestion. It would have been interesting to explore additional SLR scenarios, however the scenario analysis was constrained due to time and funding limitations, which in turn depend on the preferences of the stakeholders. As a result, it has been agreed with the Municipality of Rimini to simulate only one RCP scenario (RCP 4.5, selected as the "average"), but to consider a wider range of flood probabilities in term of return periods (i.e. 1, 10, 100, and 250). We think the one scenario that could be added in future work to extend recommendations is the RCP 8.5 at 2100, as the same scenario at 2050 does not differ significantly in terms of global SLR with respect to the RCP 4.5, while the scenario RCP 6.0 doesn't differ in terms of SLR significantly also at 2100.



Line 150-152: It is stated that “We consider the intermediate emission scenario RCP 4.5 (Thomson et al. 2011), projecting an increase in MSL of 0.53 m at 2100.” Is this taken from the same reference, i.e., Thomson et al, 2011? I cannot find this in the relevant reference. Or is this calculated by the authors? If not please give the reference.

- Thomson reference only provides general description of the RCP4.5 emission scenario features, but all cited projections refer to previous reference (Vousdoukas et al 2017). We recognize this can be ambiguous, so Thomson reference was removed for clarity.

Line 150-152: Moreover, IPCC AR5 SLR projections give more local projected values of SLR. Apart from using a generic Global Mean Sea Level rise projection for the Mediterranean area, it would make more sense to account for more regional/local SLR values at specific coastal areas (as in IPCC AR5).

- Thank you for your valuable comment. We believe that in our analysis we do account for both local SLR historical observations at coast and specific downscaled projections for the central med basin. We have taken into consideration your comment and have amended par 3.3 to address these points more clearly:

The long availability of tide gauge data along the N Adriatic coast allows to assess the changes in MSL in the last century. Records from the gauge station of Marina di Ravenna show an eustatic rise of 1.2 mm per year from 1890 to 2007, in good agreement with the eustatic rise measured at other stations in the Mediterranean Sea (Tsimplis and Rixen 2002; Carbognin et al. 2009). The projections of future MSL account for sea thermal expansions from four global circulation models, estimated contributions from ice-sheets and glaciers (Hinkel et al. 2014) and long-term subsidence projections (Peltier 2004). The ensemble mean is chosen to represent each RCP for different time slices. The increase in the central Mediterranean basin is projected to be approximately 0.2 m by 2050 and between 0.5 and 0.7 m by 2100, compared to historical mean (1970-2004) (Vousdoukas et al. 2017). We consider the intermediate emission scenario RCP 4.5, projecting an increase in MSL of 0.53 m at 2100. It must be noted that these projections, although downscaled for the Adriatic basin, do not account for the peculiar continental characteristics of the shallow northern Adriatic sector, where the hydrodynamics and oceanographic parameters partially depend on the freshwater inflow (Zanchettin et al. 2007).

The dataset obtained from [Vousdoukas et al \(2017\) - Extreme sea levels on the rise along Europe’s coasts](#) currently represents the best SLR estimate available for EU countries:

Projections of RSLR indicate a statistically significant increase in MSL along the entire European coastline. The average RSLR across Europe is projected around 21 and 24 cm by the 2050s under RCP4.5 and RCP8.5, respectively. RSLR is projected to accelerate during the present century under both RCPs, reaching 53 and 77 cm by the year 2100 [...]. The RSLR projections show higher model agreement for the Mediterranean Sea and the Atlantic coast [...].

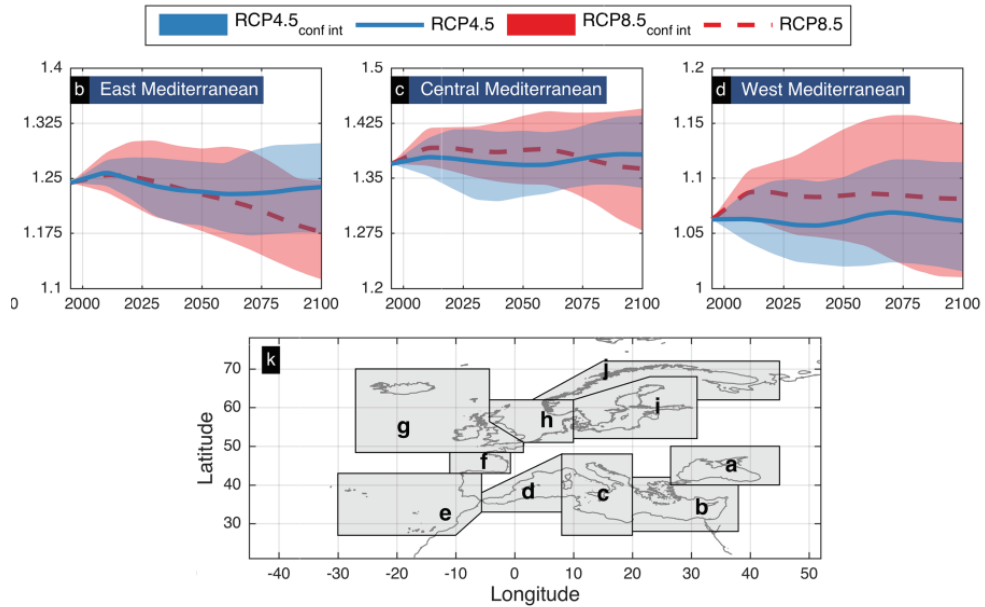


Figure 6. Time evolution of the 100-year η_{w-ss} under Representative Concentration Pathway (RCP)4.5 and RCP8.5. Lines express the ensemble mean and colored patches the inter-model range (best-worst case). In order to understand better the spatial variations of the projections, the European coastline was divided in 10 geographical regions (see k), and values shown in (a–j) result from averaging all the information from each region.

Table 1. Table Summarizing the Projected Absolute and Relative Changes of the 100-Year Event ESL (Δ ESL and $\% \Delta$ ESL) Under RCP4.5 and RCP8.5, During the Years 2050 and 2100

Area	RCP45-2050			RCP45-2100			RCP85-2050			RCP85-2100		
	Δ ESL (m)	$\% \Delta$ ESL	$\% \Delta \eta_{w-ss}$	Δ ESL (m)	$\% \Delta$ ESL	$\% \Delta \eta_{w-ss}$	Δ ESL (m)	$\% \Delta$ ESL	η_{w-ss}	Δ ESL (m)	$\% \Delta$ ESL	$\% \Delta \eta_{w-ss}$
Black Sea	0.25	18.6	7.9	0.60	44.2	4.2	0.27	19.7	5.0	0.81	60.1	1.1
East Mediterranean	0.20	14.3	-5.9	0.53	38.8	-1.1	0.22	16.0	-6.7	0.71	52.3	-8.6
Central Mediterranean	0.19	12.1	-0.8	0.53	33.4	2.5	0.24	14.9	8.6	0.75	47.8	-0.9
West Mediterranean	0.20	15.8	-1.1	0.51	41.0	-0.3	0.24	19.7	9.6	0.75	60.7	2.5
S-North Atlantic	0.18	4.9	-13.8	0.48	12.9	-17.8	0.18	4.9	-29.2	0.66	17.8	-19.4
Bay of Biscay	0.18	4.0	-10.3	0.53	11.6	-9.2	0.22	4.9	-8.2	0.80	17.4	-1.6
N-North Atlantic	0.27	4.7	28.9	0.64	11.3	13.8	0.29	5.2	27.5	0.88	15.7	17.0
North Sea	0.35	7.9	53.5	0.75	17.0	27.4	0.35	7.9	32.4	0.98	22.1	20.2
Baltic Sea	0.27	12.9	58.9	0.55	26.2	31.3	0.31	14.8	65.4	0.88	42.3	36.9
Norwegian Sea	0.21	5.1	18.1	0.46	11.2	9.5	0.23	5.7	-0.8	0.64	15.4	-5.8
Europe	0.25	8.3	18.5	0.57	19.4	9.5	0.27	9.2	15.7	0.81	27.3	7.1

ESLs, extreme sea levels; RCP, Representative Concentration Pathway.
 $\% \Delta \eta_{w-ss}$ expresses how much of the projected change can be attributed to changes in extreme waves and storm surges, considering again the 100-year event.

(Vousdoukas et al. 2017)

Line 177-179: This is a minor comment, however, is there a need for using 1 m resolution for inland topography, while using 2m resolution for the coastal area, which is more significant for an inundation model?

- Unfortunately, this is the original availability of DEM resolution provided by the Ministry of Environment: the coastal DEM was produced at 2 m resolution, while the inland river network uses 1 m resolution.

Line 228: The authors mention “wave setup” and “wave runup” throughout the paper inconsistently. Although interconnected, these ESL contributors are different parameters. A clear definition is needed how wave setup OR wave runup was calculated for the coastal flooding purposes.

- Thanks for highlighting this, the wording has been fixed in text, tables and figures. We added explanation in par 3.6 that we only consider the Wave Setup component and included the limitation of 2D hydrodynamic models not being able to resolve vertical convection and breaking waves.

Line 245: The population is only accounted for the year 2011? Is this dataset also used for years 2050 and 2100? Please address this more clearly.

- We have amended text explaining that exposure is kept static in our assessment, thus allowing for a comparison focused on the effects of different hazard scenarios. Factors such as the potential increase in tourism and changes in urban mobility due to the urban renovation project could affect the population and urban growth dynamics at the future scenarios, but this is out of the scope of the current study.

Line 280: A reference is needed for “6M Eur per km” statement.

- Thank you for this important comment, the section about costs has been extended with all the justifications from official referenced sources in par. 3.8; numbers were also updated in the analysis.

Line 285: Please mention the sensitivity analysis for “r” values (which is Appendix A) conducted within this paragraph.

- Agreed, it is now mentioned in the section about discount rate (Annex 1).

Line 310-311: The authors state that “The north-western part and the marina are not affected by the coastal renovation project.” Please specifically address this statement why and between which scenarios and years, referring to the figure 6.

- We made the sentence clearer:

The north-western part and the marina are outside of the defended area; these areas are therefore subject to a similar amount of flooding across scenarios (defended and undefended).

Line 363: The authors found that the Benefit-Cost-Ratio is 0.82 for Rimini and claim that this is profitable. According to the definition they have given between lines 292-294, it is not, at least by the year of 2100, as it is lower than 1? Please reconsider this statement.

- We appreciate your valuable comment, which is indeed correct. We have amended the text by explaining that the Cost-Benefit-Analysis that has been performed is a DRR-specific analysis in the sense that it considers only the benefits of avoided direct impacts due to coastal floods. As included now in the manuscript, we argue that our results clearly indicate an overall profitability of the defence structure implementation over the long term for Cesenatico. For the case of the municipality of Rimini, further investigation is suggested in order to holistically account for the benefits of the seafront renovation project which would likely produce better CBA results:

For instance, the potential reduction in indirect losses in terms of capital and labour productivity due to less frequent and less intense flooding events, and the potential increase in tourism and well-being of citizens due to renewed urban landscape, are

factors that could be accounted for in a holistic CBA analysis and would likely return a shorter payback period.

Technical Comments:

Line 94: "... occasions, ..." Please add comma.

Line 129: "... industrial boom." Please delete the comma.

Line 189: "Figure 3. Prototype..." Please correct with the capital letter.

Line 293: "... and the costs; ..." Please correct.

Line 359: "In figure 10 ..." Please correct.

- All spelling and grammatical errors pointed out by the reviewers have been corrected.

We look forward to hearing from you regarding our submission and to respond to any further questions and comments you may have.

Sincerely,

Amadio Mattia

Essenfelder Arthur H.