Urbino 29 July 2017

Dear Editor,

please find below our response to the Reviewers comments on paper <u>"Sea-level rise along the Emilia-Romagna coast (Northern Italy) at 2100: scenarios and impacts"</u> by Luisa Perini *et al*. (ms No.: nhess-2017-82).

For your convenience, the Reviewers' queries, reported in *italics*, have been numbered as **Qx.y,** where **x** is the Reviewer (**x**=1, 2) and **y** is the point raised. Our response is labeled by **Ax.y**. To facilitate the readability, in the marked manuscript, the answers labels are annotated on the margins.

Most of the references suggested by Reviewer 2 at the end of his letter have been included in the Bibliography in the revised version of the manuscript. Following the suggestions of Reviewer 2, a Discussion section has been added.

Various minor edits have been made throughout the manuscript to improve the presentation; all these are marked in **bold face** but not annotated on the margin. In the marked manuscript, with **[…]** we denote removed text.

We believe that the paper ha greatly benefited from the comments of the two Reviewers.

We hope that this revised version will be suitable for publication, possibly after another round of review.

Sincerely yours

Giorgio Spada (on behalf of all co-authors)

Review 1 (Anonymous)

Q1.0 *It is an interesting paper that illustrates the consequences of mean sea level rise and storminess on the coastal areas of Emilia-Romagna in terms of land loss. The paper is logically structured and the methodology seems adequate (but I cannot make comments on the flood model because I don't know it). Unfortunately, the paper often contains confusing terminology that makes it hard to understand. This problem should be solved before the paper can be published.*

A1.0 We thank the Reviewer for his positive response. We acknowledge that the terminology is confusing in some parts of the manuscript, and we have made efforts to improve it.

Main problems.

Q1.1 *a) The authors use 'sea level' both for a long term (multi-decadal) mean and a short term (e.g. hourly) value, as in the case of storm surges. For instance at page 3, line 19, the meaning is 'mean sea level', like at page 9, line 8 (case CS1), where the full 'mean sea level' is used. By contrast, at page 6, line 18, the meaning is 'sea level height' relative to a known reference. As another example, at page 10, line 5, the authors only consider storm surges, while case CS2 also includes the wave effect. Definitions should be clear and used consistently. Note that Sect. 2.2 should involve the 'mean sea level'.*

A1.1 We recognise that the terminology regarding "sea level" may be inconsistent in some cases: now we have checked the terminology throughout the whole paper.

Q1.2 *b) The use of 'wave' is also often unclear. For instance, 'storm waves' at page 6, line 19 are clearly wind waves, while 'meteo-marine wave' and 'specific waves' (same page, line 30) are undefined. Please specify when wind waves or any other wave type are involved.*

A1.2 We thank the reviewer for the remark. Now "waves" is specified correctly, where needed, to avoid ambiguous statements.

Q1.3 *c) The authors deal with both storm surges and wind waves (case CS2). Sect. 2.3 is devoted to storm surges, but something about wind waves is also included. This is confusing because the role of wind waves is first mentioned explicitly only at page 10, line 16. The authors might consider to deal with storminess in general, that is*

both storm surges and wind waves (see page 8, line 23), and introduce the subject accordingly.

A1.3 We propose to entitle Section 2.3 "Coastal storms", to include both storm surge and waves. The terminology has been changed accordingly throughout the paper. We have now quoted Harley (2017) for the definition of coastal storm.

Q1.4 *Page 1, line 1: Are there any reasons to neglect natural land subsidence?*

A1.4 There is no reason to neglect natural land subsidence, effectively. Now we refer to "subsidence", without limiting ourselves to "human-induced".

Q1.5 *Page 1, line 13: Please clarify that '(in_CoastFlood)' is the name of the model. The missing reference, the different typos and the brackets are confusing.*

A1.5 This has been fixed in the revised manuscript, in order to clarify that '(in_CoastFlood)' is the name of the model.

Q1.6 *Page 4, Lines 15-16: 'some cases . . . sometimes' is redundant.*

A1.6 We agree: "sometimes" has been removed.

Q1.7 *Pages 5-6, Sect. 2.2: The discussion of mean sea-level changes over thousands of years is not crucial for present and future variations. By contrast, there is no discussion on the mean sea level variations during the last 100 years or so, when also anthropogenic subsidence occurred.*

A1.7 Effectively, a discussion on the mean sea level variations during the last century was missing. We have added a paragraph on this subject, with reference to recent works about the history of sea level in the Adriatic Sea during last century, due to its relevance with the topics dealt with in the paper. The section "Sea level variability" has benefited significantly from there modifications, in our opinion.

Q1.8 *Page 6, lines 17, 30: The exact meaning of 'meteo-marine' is unclear in this context. I guess that the authors mean 'the sea level changes component related to the atmospheric forcing', which includes both wind and atmospheric pressure (not*

mentioned). This component is the 'residual sea level' also known as the 'meteorological tide'. Moreover, is this the 'non-tidal residual' at line 26?

A1.8 The entire section 2.3 has been reorganised, and the terms used have been defined in a more thorough way. The term meteo-marine has been avoided and substituted with a more clear terminology.

Q1.9 *Page 6, line 27: Please quote the reference to which the reported heights are measured.*

A1.9 The heights are referred to mean sea level, and this has been explicitly quoted in the revised manuscript.

Q1.10 *Page 6, lines 29-31: Unclear. I understand (but I am not sure) that the observed sea level can differ from the forecast represented by the astronomical tide plus the residual sea level ('meteo-marine wave' is bad terminology). The difference does not occur because of local morphology and specific waves, but because the model used for the predictions is not good enough. For instance, it may not include the correct basin bathymetry and coastal morphology, or the atmospheric forcing is too coarse. Anyway, the sentences can be dropped.*

A1.10 Our purpose is exactly to enlighten the limitations of the model. Instead of dropping the sentences, we have preferred to improve them, making a specific reference to the coarse resolution of the model in respect to the local morphology.

Q1.11 *Page 6, line 32: Both waves and tides are mentioned. It is not clear what 'tides' mean here.*

A1.11 Effectively here we refer to storm surge, meaning tide+surge. See also comment on Q1.3.

Q1.12 *Page 7, line 6: Do the authors mean Adriatic instead of Italy? Page 8, line 5: Unclear sentence. What are 'the E-R coast values'?*

A1.12 Our apologies. Another example of sloppy terminology. It has been fixed. We refer to the Northern Adriatic coast. With have also specified that "E-R coast values" refers to sea level rise at E-R coast.

Q1.13 *Page 9, line 14: The IPCC mean sea level rise projections are made for 2081-2100 (central year 2090.5) relative to 1986-2005 (central year 1995.5) (page 7, line 26), that is a 95-year time period, but the authors use a 85-year period. Is that a mistype?*

A1.13 The 85 years time-span is the consequence of different epoch for the subsidence model with respect to that of the sea level. We understand that this could be misleading and we rephrased the statement omitting this length of the used time-span.

Q1.14 *Page 12, line 9: Is 'sea-level component' quoted in comparison to subsidence? Please clarify.*

A1.14 We have now specified "in comparison with subsidence".

Q1.15 *Page 14, line 29: Does the model include wind waves set up? These are not mentioned here, while they seem to have been at Page 10, line 16, when they are distinct from the surge.*

A1.15 See point Q2.6 below.

Q1.16 *Page 15, line 33: The authors should not only say that subsidence rates are assumed unchanged in the 21st century, but also the storminess characteristic.*

A1.16 We agree; this has been specified in the revised manuscript.

Q1.17 *Page 21, Fig. 2: Please say if the zero height in the map corresponds to the 1986- 2005 mean sea level (the IPCC start time), to the zero of the Italian geodetic network or to another thing. I also suggest to use a colour palette that highlights the altitude differences in the low-lying areas. Probably, a 0 m contour could also be useful.*

A1.17: The reference height in the map is the zero of the Italian geodetic network. In our opinion the current color table highlights well the elevation differences in low-lying areas.

Q1.18 *Pages 26-30, Fig. 7-11: The coloured areas are often small compared to the whole figure and most of them are barely visible. Can the authors improve their visibility?*

A1.18 We agree; in Figures 7-11 the coloured areas are small. We improved the overall quality of figures, from 6 to 10 (new numbering); the current version of manuscript includes these new versions of figures. If necessary, we shall provide higher resolution maps in a later stage of the editing process.

Q1.19 *Page 33, Table 4: In the text (page 10) rare events have a return period »100 years, not >100.*

A1.19 We agree, now it is ">>100".

Review 2. G. Le Cozannet

Q2.0 *The article by Perini et al. provides an estimation of sea-level rise impacts (in terms of erosion and flooding in the Emilia-Romagna region). Interestingly, the article considers regional subsidence patterns, which have a high spatial variability as shown by previous observations based on SAR interferometry. The article also illustrates how the application of European directives can stimulate studies and discussions regarding the future impacts of climate change. Overall, I think that the article provides an interesting perspective, and that it is relevant to NHESS. What is missing, to my opinion in the article, is a real discussion of the significance of the results and their implications. I can suggest a few recommendations in this respect:*

A2.0 We thank the Reviewer for his positive response. We acknowledge there is room to improve the manuscript, especially regarding the implications of the results.

Q2.1 *- It could be interesting for the reader to know how such work (which is apparently strongly connected to regulatory processes such as the European flooding directives, e.g. page 3 line 22) will (or is expected to be) integrated in regional to local adaptation. I have no specific suggestion here, but I just remind that the AR6 IPCC reports to come will require information on the implementation of adaptation (including its successes and limitations). I think that the authors can make a useful contribution here.*

A2.1 Something has now been said about this important point. We expect that the output of our analysis will support the planned activities for the second stage of the Flood Directive 2007/60, i.e the updating of the knowledge framework and hazard and risk maps by 2019. These should include, in fact, the risks assessment driven by the climate change, which was not been presented in the first cycle of the directive application, in order to identify mitigation and adaptation measures. Likewise, we expect that this work can provide an important contribution to the working group on the Regional Climate Change Strategy, which aims to develop an action plan by 2018. Now this is clarified in the revised manuscript, see Section Conclusions.

Q2.2 - *The authors clearly list their assumption all along their study (e.g. section 3.2), but the reader would like to see a discussion on the impacts of these assumptions in the final results. I suggest that uncertainties in the results could be given more attention in a discussion section (see below further suggestions).*

A2.2 We have decided to discuss, at least qualitatively, the possible impact of the various assumptions made in this work in a (new) "Discussion" Section. This may contribute to a better assessment of the uncertainties implicit in our study, although the establishment of quantitative error bars is out of the scope of present work.

Q2.3 - *Finally, if possible, it would be interesting to see to which extent this study agrees or disagrees with previous impacts assessments performed in the same region (e.g. Wolf et al., 2016) and why.*

A2.3 Indeed, a comparison with Wolf et al., 2016 is not straightforward, since goals and approaches of the two works are quite different. However, in the revised manuscript, we have added a specific paragraph on this issue, comparing the two approaches in a somewhat more clearly compared to our previous submission.

I provide below detailed comments, which are hopefully useful if the authors decide to discuss uncertainties: -

Q2.4 *Subsidence: I wonder to which extent it is realistic to assume that subsidence is linear in time. In practice, the authors show that it has not been the case in the past (with acceleration in subsidence rates with increased fluid extraction in section 2.1), and this seems to me relatively common in cases of subsidence caused by groundwater extractions (Le Mouelic et al., 2005; Wang et al., 2012; Raucoules et al., 2013). I wonder if the authors would agree that in their table 5, they provide the*

maximum benefits of an adaptation strategy consisting in mitigating subsidence through reduced fluid extractions.

A2.4 In the revised manuscript, the 1st paragraph of the new Discussion section addressed the issue of the constant rate of subsidence. We now quote the manuscripts suggest by the Reviewer as noticeable examples of human driven subsidence characterised by a variable rate.

Q2.5 *A small point Page 5 line 12: "compaction of sediments" is unclear to me. I assume the authors refer here to natural (and later, anthropogenic) variability of water content in various geological layers, resulting in a reduction of their volume.*

A2.5 Yes, we refer to the variability of the water content in the various geological layers.

Q2.6 *- Extreme water levels: The authors use value of water heights during storms (subsection 2.3). However, it is unclear which processes have been incorporated. Of course, the references to the project Micore and other studies suggest that tides, atmospheric surge, wave setup (Stockdon et al. 2006) have been taken into account, but I suggest naming these processes explicitly. Note that the wave setup can account for an additional contribution of several 10cm, which is not negligible considering the magnitude of sea-level changes to come. If no information is available on this process, this source of uncertainties can be assumed dominant for the decades to come.*

A2.6 The processes that have been incorporated are shortly mentioned in Section 3.3.2 (description of case study CS2). They include the wave set up, effectively. We have included more information at the end of section 2.3 in the revised manuscript. The meaning of S_STS is well explained in words just after equation (6), and a new equation is probably unnecessary.

Q2.7 *- Mean sea-level projections: Sea-level projections used in this article rely on global models, which have not the ability to represent processes taking place at the Gilbratar straight (subsection 2.4). This can result in deviation of some 10 cm from sea-level projections in the Atlantic, west of the Gibraltar straight. Also, is the area affected by 3D circulation modifying water levels by +/-10cm as it is the case in the gulf of Lion? I suggest to discuss these processes in a discussion on uncertainties. They are discussed for example in Adloff et al. (2015, 2016, both in Climate*

Dynamics) and also in our article Le Cozannet et al. (2015 in Environmental Modeling and Software).

A2.7 This limitation has been addressed in the (new) Discussion section, where we also account for some of the literature suggested by the Reviewer, which we acknowledge particularly for having done this important point.

Q2.8 *Furthermore, the wording "Worst" or "best" cases scenarios (page 9 line 22 and several times after) is not appropriate for ranges of uncertainties representing likely confidence intervals (see Church et al., 2013a, 2013b) and can be misleading for coastal managers in charge of adaptation (Hinkel et al 2015). This should be rephrased.*

A2.8 Here and in the following, we propose to use the wording "HIGH-END" and "LOW-END" instead of "worst" and "best", respectively. The notation for the various equations has been changed accordingly. We hope that this new wording is now suitable, and compatible with Hinkel et al's, otherwise we are looking forward to have new suggestions from the Reviewer. Note that I have now realised that in the insets of Figures 6-10, the previous adjectives "worst" and "best" appear. We shall fix this problem at a later stage of the review process.

Q2.9 *- Impacts : The authors have presented their results in two ways : "land losses" due to sea-level rise and subsidence (e.g., conclusion) and "areas lying below mean sea-level" (e.g. in table 5). I am personally in favor of the second formulation, as it makes no assumption on the adaptive responses to come (e.g., beach and dunes nourishment. . .). In both cases, the results assume no morphological changes, which, again, would deserve a discussion. There is a huge bibliography in this area.*

A2.9 Regarding the morphological changes, it was chosen to consider a rigid substrate modified only by the subsidence (translation), since, at present, it has not been possible to apply a dynamic modelling approach integrating also long term coastal evolution (e.g. beach changes) at the regional scale, or land use projection. In this view, the model excludes the natural adaptation of the coastal system as well as it funds on the assumption of "no intervention" by man (no nourishment, no upgrading in coastal defense systems, etc.). In the discussion Section, these points are addressed. Unfortunately, at the current stage we cannot assess the level of uncertainty due to the assumption made.

Q2.10 *Finally, can the authors explain why storm surge impacts have not been assessed in both CS1 and CS2 hazard assessments (page 14 line 5)?*

A2.10 With this choice we aim at studying the possible future coastal morphological framework and the effects of the sea storms separately.

Q2.11 *Finally, I wonder if figure 3 and 5 could be merged.*

A2.11 In an effort to improve all the figures of the paper, after several attempts, we have merged (previous) Figure 2 (the DTM) with (previous) Figure 3 (the subsidence map) to obtain (new) Figure 2. The other figures have been improved in minor details (and of course renumbered accordingly) and in the overall resolution so that fine details can hopefully better captured. See also point Q1.18 above.

I hope these comments are useful.

The suggestions have been useful and we believe that the manuscript has seen a significant improvement thanks to the help of both Reviewers.

Most of the following references, suggested by Reviewer 2 have been discussed and included into the Bibliography in the revised version of the manuscript.

References

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Sea-level rise along the Emilia-Romagna coast (Northern Italy) at 2100: scenarios and impacts

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Abstract. As a consequence of climate change and **land subsidence**, coastal zones are directly impacted by sea-level rise. In some particular areas, the effects on the ecosystem and **urbanisation** are particularly enhanced. We focus on the Emilia-Romagna coastal plain in Northern Italy, bounded by the Po river mouth to the north and by the Apennines to the south. The plain is ∼130 km long and is characterised by wide areas below **mean sea level**, in part reclaimed wetlands. In this context, several morphodynamic factors make the shore and back-shore unstable. During next decades, the combined effects of land subsidence and of the sea-level rise in consequence of climate change are expected to enhance the shoreline instability, leading to a further retreat. The consequent loss of beaches would impact the economy of the region, tightly connected with tourism infrastructures. Furthermore, the loss of wetlands and dunes would threaten the ecosystem, crucial for the preservation of life and environment. These specific conditions show the importance of a precise definition of the possible local impacts of the ongoing and future climate variations. The aim of this work is the characterisation of vulnerability in different sectors of the coastal plain and the recognition of the areas in which human intervention is urgently required. The IPCC AR5 sea-level scenarios are merged with new high resolution terrain models, current data for local subsidence and predictions of the **flooding model `in_CoastFlood` in order to** develop different scenarios for the impact of sea-level rise to year 2100. First, the potential land loss due to the combined effect of subsidence and sea-level rise is extrapolated. Second, the increase of floodable areas in consequence of storm surges is quantitatively determined. The results are expected to support the regional mitigation and adaptation strategies designed in response to climate change.

1 Introduction

The sea-level rise associated with global warming is a growing concern for the scientific community, as well as for governments, the media and the public. Climate-driven sea-level rise has a direct impact on the coastal zones, **with** threatening consequences on the ecosystem and **urbanisation**. The causes of contemporary sea-level rise have been reviewed by Nicholls and Cazenave (2010), who have also identified, globally, the coastal areas that are particularly vulnerable to flooding. These include low-elevation coastal zones, densely populated areas where the natural or human-induced rate of subsidence is appreciable, and regions characterised by a limited adaptation capacity. In addition, higher **mean sea levels** are expected to amplify flooding caused by storm surges and hurricanes, with an enhanced impact on population (Nicholls et al., 1999). The last Inter-

governmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) has made a considerable progress toward an understanding of the 20th century sea-level rise and its variability on a global scale; furthermore sea-level projections for the 21th century have been greatly improved (Church et al., 2013). Nevertheless, detailed projections of sea-level rise at regional and local scale are still hampered by the complex local response of the coastal system to sea-level rise (Cazenave and Cozannet, 2014; Hinkel et al., 2015).

In the general context outlined above, this work focuses on the possible effects of sea-level rise on the coastal area of Emilia-Romagna (Northern Italy), one of the administrative regions of Italy facing the Northern Adriatic Sea (see Figure 1). F1 The Emilia-Romagna (E-R) coastal plain has a crucial economical and naturalistic value. It is, indeed, the site of one of the largest tourism industries in Europe, the *Riviera Romagnola*, and it embraces the Po Delta protected area, which was recently included in the Man and the Biosphere Programme by Unesco[1]. Characterised by a gentle slope, the E-R coastal plain is high vulnerable in consequence of *i)* widespread coastal erosion, *ii)* seawater intrusions related to sea-level rise, *iii)* storm surges and *iv)* land subsidence. These four major threats have been exacerbated by the human pressure that took place since the 1940s, when a rapid urbanisation and a strong exploitation of underground resources (water and gas) initiated (Lorito et al., 2010; Perini and Calabrese, 2010). The reader is referred to the recent work of Aucelli et al. (2016) for the risk assessment of coastal inundation in another Italian **area *i.e.,* the Volturno coastal plain in southern Italy, characterised by spread back-shore depressions and subsidence**. **On a nationwide scale, a** detailed account for sea-level rise and potential drowning of the Italian coastal plains has been given by Antonioli et al. (2017). **Finally, a sophisticated** approach was taken by Wolff et al. (2016) who downscaled the Dynamic Interactive Vulnerability Assessment (DIVA) model (Hinkel et al., 2014) to the E-R contest. This model considers the effects of **mean sea level** rise in terms of impacts on the population and on the existing assets. It also Q1.1 foresees that mitigation actions, as the building of dykes, will gradually accompany the sea-level rise to year 2100.

The awareness by the local authority *i.e.,* **the Emilia-Romagna Regional Administration**, that a holistic approach was desirable to properly manage the climate-related risks at coastal areas, motivated the set up of an integrated path, called "Gestione Integrata delle Zone Costiere" (GIZC) which led to the approval of specific guidelines[2]. The document recognises the need of putting the mitigation of local risk in the climate change framework, with a special attention to the sea-level rise issue. Subsequently, in 2007, the EU delivered the so-called "Floods Directive[3]" **(FD) (European Parliament and Council, 2007) aimed at reducing and managing** the risks posed by **floods to human** health, the environment, cultural heritage and economic activity. The recent Italian Environmental Ministry guidelines on coastal protection from erosion and climate change effects[4], delivered in cooperation with coastal regions in 2016 and in accordance with the FD, also highlight recommendations of the Emilia Romagna GIZC guidelines. The document remarks that long term **climate change** could not be excluded from the national and regional plans for the mitigation of the seawater flooding risks. These concepts are also included in the nationwide SNAC (National Strategy for the Adaptation to Climate Change)[5]. The development of these national and transnational laws

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[1]See goo.gl/gi1yNE

[2]"*Linee Guida GIZC*", deliberation of Regional Council n. 654/2005.

[3]Directive 2007/60/EC on the assessment and management of flood risks (goo.gl/pzJ74o).

[4]*Linee Guida Nazionali per la difesa della costa dai fenomeni di erosione e dagli effetti dei cambiamenti climatici* (goo.gl/QAL8iN)

[5]*Strategia Nazionale di Adattamento ai Cambiamenti Climatici,* 2014 (goo.gl/zCYV6C)

and guidelines drove the definition, **by the** Emilia-Romagna Regional Administration, of the "Path toward a strategy for the mitigation of climate changes[6]". This path includes the study **of the climate change impact on coastal zones** and the identification of the most vulnerable areas by means of models and cartographic analyses.

Within the multidisciplinary pathway above, it is crucial to identify and characterise the most vulnerable portions of the coastal plain, on which prevention and mitigation actions should be focused at first. Local and short term phenomena occurring in the E-R coastal plain and in its neighbourhoods have been put in a long term framework, which also includes regional and global climate change. The attention on the combined effects of climate-induced sea-level rise, of subsidence and **coastal storm events along E-R shoreline arouse** two decades ago, following the 1992 IPCC Supplementary Report (Intergovernmental Panel on Climate Change, 1992). Bondesan et al. (1995) preliminarily investigated the impact of these IPCC scenarios for sea-level rise to year 2100, in combination with expected subsidence and trends for storm surges. They concluded that the area potentially affected by the risk of flooding was doomed to increase in the future. **Along these lines,** in the work of Gonella et al. (1998) a numerical model based upon geographical information system (GIS) tools was applied **for the first time** to the 1992 IPCC scenarios, considering storm surge return periods of 1, 10, and 100 years. **Their** analysis was also extended to the risk assessment in terms of saltwater ingression and soil consumption. Recently, Antonioli et al. (2017) have used IPCC AR5 global projections at 2100 for sea-level rise with local assessment for subsidence derived from GPS and TG data. These have provided regional scenarios for different parts of the low elevation portion of the Italian peninsula, including the E-R coastal plain.

The main purpose of this work is the determination of the future impact of land subsidence and sea-level rise on the E-R coast. In particular, for the first time in this region, the focus will be on two aspects: *i)* the loss of territories that are currently at, or above, **mean sea level** (**case** study #1, CS1) and *ii)* the enlargement of the areas potentially affected by seawater flooding (**case** study #2, CS2). Our objective is twofold: *i)* the identification of those portions of the E-R coast which potentially could be flooded by the end of current century in the occasion of storm surges, and *ii)* the comparison of the results with the current hazard map for the ingression of the sea that resulted from the **[...] FD**. In the following, CS1 and CS2 will be discussed taking the geomorphological and geodynamic complexity of the area into account, and adopting the **mean sea level** projections published in the **IPCC AR5** (Church et al., 2013).

The paper is organised as follows. **Section 2 describes the physical characteristic of the study region and the driving processes. The data and methods employed are presented in Section 3. The results, presented in Section 4, are discussed in Section 5.** Our conclusions are drawn in Section 6.

2 Physical characteristics and driving processes

The E-R coastal plain develops along the south-eastern margin of Po Valley in Northern Italy; it is bounded to the north by the Po di Goro branch of the Po Delta and to the south by the Apennine Chain. The orientation of the chain and the direction of progradation of the Po River make the plain narrow to the south (a few kilometres in the EW direction), and broad to the north

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[6]Deliberation n. 2200/2015, *Percorso verso una strategia di mitigazione dei cambiamenti climatici.*

where it exceeds **40** km (see Figure 2, **left frame**). The shoreline is about 130 km long and is characterised by low-elevation sandy beach ridges, occasionally associated with lagoons, wetlands and river mouths. F2L

The coastal area and its shoreline can be divided into a northern (N) and a southern (S) sector, whose boundary can be placed around the town of Cervia (see Figure 1). The different physical characteristics of the two sectors, which are of relevance for
5 the determination of the response of the coastal area to the marine ingressions, are detailed in Perini and Calabrese (2010). The vulnerability of the entire coastal area is mainly caused by the absence of dunes and by their discontinuity, especially in the S sector. A further cause of vulnerability is the presence, particularly in the N sector, of wide areas that are **currently below mean sea level**. Moreover, the combination of subsidence with the natural retreat of the shoreline due to the reduction of the Q1.1 river sediment discharge is responsible for a widespread coastal erosion, both on short and long term time scales (Perini and
10 Calabrese, 2010).

The human pressure and the underground exploitation of the E-R coastal plain and of its surroundings have enhanced the expected effects of climate change, and particularly of **coastal storms**. The risk for sea flood has been magnified by the urbanisation that, since the end of the second World War, was increased by ∼400% in terms of occupied area (Lorito et al., 2010). In front of most coastal towns and resorts the dunes, which are the natural rampart against the sea flood and a natural
15 reservoir of sand for the nourishment of the beaches, have been totally destroyed by urbanisation. In some cases the **shorelines retreat have** reached the buildings and infrastructures. This urbanisation, besides, is mostly concentrated along a narrow area Q1.6 along E-R coastal plain, bordering on the zone where normally most of the energy is dissipated during intense **coastal storms**.

The Emilia-Romagna shoreline is highly artificialized and shows different types of coastal flood defences. These are mainly composed by emerging or submerged longitudinal breakwaters and localised jetties, groynes and seawalls, especially in the
20 Goro lagoon. In the N sector, following the extreme flooding event that occurred in 1966 (Perini et al., 2011), a long, 4 m high embankment was erected to protect the back-shore, at a distance ranging between 0.5 and 1.5 km from the shoreline. However, during the 1970s and 1980s, the vulnerability of the area between the shoreline and the wall was not considered a concern and an intensive urbanisation took place there. In the S sector, on the other hand, no coastal defences has been erected against marine inundations, while the sparse flood protection dykes are only aimed to defend local infrastructures from **coastal storms**.
25 Against the **coastal storms**, it is common practice off-season (*i.e.,* during the winter) to build temporary embankments along the beaches. These, if properly designed, play a crucial role in the attenuation and mitigation of the effect of **coastal storms**, in reducing the ingression of sea water in the back-shore and in preventing erosion.

For each of the two sectors considered (N and S), the physical features of the E-R coastal plain are summarised in Table 1. T1 These include the main geometrical features (the coastal plain width D and its elevation above **mean sea level** H), geomor- Q1.1
30 phological characteristics, shapes and tendency, shoreline width D_S and average width $\bar{D}_S$, and shoreline backside usage. Furthermore, **in the following of this Section**, we provide an account of the processes that are responsible for the coastal vulnerability of the area. These are: *i)* land subsidence, *ii)* sea-level variability, and *iii)* storm surges.

2.1 Land subsidence

For those areas slightly above **mean sea level**, the main consequence of subsidence is an increased vulnerability to the effects of storm surges, since the progressive lowering of the ground below **mean sea level** will facilitate the marine ingression. Current average rates of land subsidence observed in the S sector of the E-R coastal plain, as well as in the southernmost part of the N sector, are close to 5 mm yr^{-1}. However, in some areas of the S sector and particularly at the mouths of rivers and in the back-shore of the Cesenatico and Rimini areas, they may exceed ∼10 mm yr^{-1}. In the N sector, rates of subsidence are smaller, typically in the range of 0 to 2.5 mm yr^{-1}, while in the area of the Po Delta rates of ∼10 mm yr^{-1} are again observed (Arpa-RER, 2012) (see Figure 2, **right frame**). Locally, land subsidence reaches 20 mm yr^{-1} due to gas extraction. This occurs, in particular, at the Fiumi Uniti river mouth. These significant present-day rates can result in a total subsidence of 2-3 meters in a century (Bondesan et al., 1995), as a consequence of the combined action of natural and anthropogenic factors.

The natural component of land subsidence is normally the result of tectonic activity, Glacial Isostatic Adjustment (GIA) and **sediments compaction caused by the variability of water content in various geological layers, resulting in a reduction of their volume.** Various works have investigated the geological and tectonic evolution of the area (Pieri and Groppi, 1981; Ricci Lucchi et al., 1982), the effects of GIA (Lambeck et al., 2011), and the quantification of subsidence in the Po Plain and in the Northern Adriatic coast (Carminati and Di Donato, 1999; Gambolati et al., 1999; Antonioli et al., 2009; Teatini et al., 2011a). These studies have concluded that the natural subsidence in the study region is dominated by the effect of sediment compaction that, along the costal belt, can reach levels comparable to the anthropogenic component of land subsidence. Furthermore, subsidence of glacial isostatic origin has been shown to have presently a minor role along the E-R coastal plain (Stocchi and Spada, 2009).

The anthropogenic subsidence is a consequence of land use and soil exploitation that followed the second World War and is mainly caused by water pumping and gas extraction. These activities have produced a rapid increase of ground subsidence, with rates sometimes exceeding the natural values by one order of magnitude. For example, in the municipality of Ravenna, the observed rate of subsidence rose from 5 (pre-war epoch) to ∼50 mm yr^{-1} (after the war). A detailed discussion of the subsidence connected with the extraction activities can be found in Barends et al. (2005), Teatini et al. (2005) and Arpa Ingegneria Ambientale (2008). At present, following the reduction of most of the water extraction activities, the extraction induced subsidence is mainly attributable to gas fields (Angela-Angelina, see Figure 1), which are still in production. A comprehensive map of the expected regression for the Northern Adriatic coastline at 2100 was published by Gambolati et al. (1998). They also estimated the extent of the floodable area in consequence of the combined effects of subsidence and of a 50 cm increase in **mean sea level**, based upon a coarse DTM dataset (see Figure 1.18 in Gambolati et al., 1998).

2.2 Sea-level variability

During last millennia, the history of the E-R coast, as well as the Adriatic Sea, has been characterised by a significant sea-level rise and variability. In response to the rapid sea-level rise following the end of the last ice age, in the early Holocene the shoreline experienced a rapid migration from the current latitude of Pescara to approximately the present-day position of

the coastline (Correggiari et al., 1996) (see Figure 1). This was followed by a stabilisation of the shoreline close to its present position, although it has been recognised that, during the post-glacial period, small changes in the climate and in the eustatic component of sea level occurred at scales of decades and centuries (Bruckner, 1890; Friis-Christensen and Lassen, 1991). The migration of the shoreline toward the current position initiated between $4,000$ and $5,000$ years ago, driven by the progradation of the Po river delta and of the beach ridges. During this period, a slow subsidence was acting against the retreat of the sea water (Correggiari et al., 1996).

At time scales of decades to centuries, changes of the shoreline have been more complex but of smaller amplitude, with shifts up to a few kilometres, mainly driven by the dynamics of rivers (Calabrese et al., 2010) and connected with the ongoing climate change. **During the last millennium,** we remark the Medieval Climate Optimum (Veggiani, 1986) with a relative maximum in sea level (IX-X century) followed by the Little Ice Age (XVI-XIX century) with larger sedimentary production and a marine regression (Marabini et al., 1993; Brázdil et al., 2005).

During last century, tide gauges located across the Adriatic Sea have indicated a regional rate of sea-level rise of 1.25 ± 0.04 **mm yr**$^{-1}$**, slightly less than the global secular average (e.g. Spada and Galassi, 2012). However, significant cyclic variations with a period of** ~ 20 **years, associated with the Atlantic decadal oscillations, have been observed as well (Galassi and Spada, 2015). Cerenzia et al. (2016) have recently studied the anomalous tide gauge record of Porto Corsini, which goes back to the late** 1880**s and shows long-term rates of relative sea-level change of** 8-9 **mm yr**$^{-1}$**. These rates, which strongly deviate from the typical rates across the Adriatic Sea (Galassi and Spada, 2015), testify an important role of local land subsidence, also driven by anthropogenic factors as water extraction and soil compaction (Teatini et al., 2005)**. Q1.7

For our subsequent analysis, it is important to remark that in the Northern Adriatic Sea the effects of GIA on relative and absolute sea-level change are presently relatively minor, *i.e.* of a few fractions of millimetres per year **(Stocchi and Spada, 2009; Galassi and Spada, 2015; Bonaduce et al., 2016)**. Future rates of GIA-induced sea-level variations across the whole Mediterranean Sea (Galassi and Spada, 2014) will not change with respect to current trends since this phenomenon only evolves on time scales of millennia.

2.3   Coastal storms

Q1.3

The entire northwestern coast of the Adriatic Sea is exposed to a high degree of inundation risk by **sudden water level increase** Q1.1 **associated with certain coastal storms (Harley, 2017).** The E-R coastal plain can be considered a low-energy environment Q1.3 with significant wave height $H_{sig} = 0.4$ m (period $T_{peak} = 4$ s) and semidiurnal and micro tidal regime, **[. . .]** with an average Q1.8 maximum excursion of 0.7-0.8 m (IDROSER S.p.A., 1996; Harley et al., 2012). **Wind waves** are characterised by a significant Q1.2 height, with $H_s = 3.3$ m for 1 year return period (Armaroli et al., 2009), **which are most frequently associated with the** *Bora* **weather conditions, blowing from east to northeast sectors. South-easterly winds (***Scirocco***) are generally not as intense** Q1.3 **as those generated by** *Bora* **winds (Deserti et al., 2006), due to sheltering produced by the Conero Headland (**~ 100 **km** Q1.8 **to the South, see Figure 1) and to the lower strength of** *Scirocco***. Nevertheless,** *Scirocco* **is the main driver of storm surge, causing the push of water all along the Adriatic Sea.**

A detailed analysis of the storm surges [. . .] was carried out by Masina and Ciavola (2011) using the tide gauge data from Porto Corsini (RA). Their analysis has identified extreme levels of 0.85, 1.05 and 1.28 m **on mean sea level** for a return period of 2, 10 and 100 years, respectively. The corresponding non-tidal residuals, computed for the same return periods, **are** 0.61, 0.79 and 1.02 m **on mean sea level**; such values are in use in Emilia Romagna Region for the computation of **total water** level in the flooding scenarios used for the FD maps (Perini et al., 2012).

Q1.9

Q1.2

Q1.9

In the occurrence of storm **surges, however, the coastal sea level** can vary significantly with respect to the predicted combination of tide and **wave**. This is consequence of **the coarse resolution of the model with respect to local morphology and of the spatial variability of wave characteristics along the coastline**. A statistical analysis of the comprehensive dataset of **coastal storms** during the period 1946-2010 (Perini et al., 2011) allowed the definition of threshold values **for wind waves and surges** above which significant events, in terms of effects on population, landscape and urban structures, were recorded (Armaroli et al., 2012). These thresholds are in use **in the "coastal alert"** procedure adopted by the E-R Regional Civil Defence Agency since 2012.

Q1.2

Q1.10

Q1.3

Q1.3

Q1.11

The stronger impacts are those associated with the coupling between winds from the first quadrant (N and NE) and exceptional tide peaks, known as *"acqua alta"* (Pirazzoli, 1981). The latter, indeed, appears to be crucial for the occurrence of the coastal flooding (Perini et al., 2011). During the observation period 1946-2010, the most critical season has been **late autumn** (November and December) while in the last five years these events have been recorded even in February. The most relevant event was that of November 1966 (Malguzzi et al., 2006; Trincardi et al., 2016), which impacted the whole Northern **Adriatic coast** (De Zolt et al., 2006). This boosted the completion of most of artificial defences currently in place along the E-R coastal plain. With respect to the damages, these events commonly affect the touristic infrastructures along the coast (*e.g.,* the resorts located along the beaches) in consequence of the combination of flooding and of beach erosion. In some cases, the effects are exacerbated by the overflow of the rivers and channels whose discharge is obstructed by the storm surge, causing flooding in the surrounding urbanised areas and consequently increasing the impact on infrastructure and population. **The complex factors outlined above have prompted us to simulate complex meteorological event scenarios, taking into account the main parameters, namely surge, astronomical tide and wave setups, which are already considered in the application of the FD.**

Q1.12

Q2.6

3   Data and Methodologies

The purpose of this work is to analyse the impact of the predicted relative sea-level change at 2100 along the E-R coastal plain. Two distinct aspects will be modelled and discussed. The first is the increase in the extension of land with elevation below **mean sea level** and possibly of submerged areas, while the second is the effect of storm surges in terms of floodable areas. In both cases, the combined effects of sea-level rise and subsidence will be properly taken into account. In **the following of this Section** we describe the sea-level projections that have been employed in this work (3.1), some fundamental assumptions in modelling (3.2), and the details of the models adopted (3.3).

Q1.1

3.1 Projected mean sea level

For an assessment of future sea-level rise, we adopt the Representative Concentration Pathways (RCP) scenarios reported in the IPCC AR5 (Church et al., 2013). By the Coupled Model Inter-comparison Project Phase 5 (CMIP5), the IPCC AR5 has defined RCPs that account for the evolution of the climate variables, and in particular of the CO_2 concentration. The RCPs are used for climate modelling to describe four distinct future climate scenarios, characterised by different amounts of greenhouse gas emission. The four RCPs 2.6, 4.5, 6, and 8.5 are named after the possible range of radiative forcing values to year 2100 relative to pre-industrial values, *i.e.* $+2.6$, $+4.5$, $+6.0$, and $+8.5$ W m^{-2} (see Van Vuuren et al., 2007; Clarke et al., 2007; Fujino et al., 2006; Riahi et al., 2007, respectively).

The global mean sea-level rise predicted for the four RCPs to 2081-2100 with respect to 1986-2005 is given in Table 2, whereas the projected sea-level rise is shown in Figure 3. Table 2 also shows values of sea-level rise expected across the Adriatic and the Mediterranean Sea, obtained by averaging the AR5 sea-level rise grids downloaded from the Integrated Climate Data Center (ICDC)[7]. We note that values of sea-level rise expected across the Adriatic Sea are systematically lower than those relative to the Mediterranean Sea. These, in turn, do not exceed the globally averaged values. Therefore, **the use of globally averaged values for the IPCC projections** like in Antonioli et al. (2017) would **overestimate**, along the E-R coast, the total amount of sea-level rise.

To focus on the Northern Adriatic Sea, we have extracted from the global AR5 maps the **mean sea level** projections for the grid cell closest to the E-R coast, namely the one centred at latitude $44.5°$ N and longitude $13.5°$ E (see Figure 1). For any RCP, the E-R coast **sea-level rise** values is found to be slightly lower than those pertaining to the whole Adriatic Sea. We are aware that in semi-enclosed basins like the Mediterranean Sea the ocean model component of sea-level rise could be affected by a limited precision, since the number of models contributing to the "ensemble mean" in these boxes is sub-optimal (Mark Carson, personal communication, 2013). However, we have kept these local projections since the members of the ensemble used to obtain them provide predictions that are broadly consistent with those in the nearby Atlantic Ocean boxes. In the Adriatic Sea cell considered, the assessed GIA component of future relative sea-level rise is -0.022 ± 0.005 m to year 2100 with respect to 1986-2005, where the uncertainty arises from the different predictions of two independently developed GIA models[8].

3.2 Assumptions

The phenomena associated with long-term sea-level rise depend on geodynamic, morphodynamic, hydrodynamic and sedimentary factors. In consideration of the challenge of creating a model that accounts for all the aspects of the problem and to limit the computational burden, we have decided to take into account only the changes in the topography due to subsidence, which is the best monitored driving process along the coast. Moreover, several assumptions are necessary to control possible sources of uncertainty, as well as to ease the interpretation of the results.

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[7]See `goo.gl/QGV5md`.

[8]See the README.txt at *ftp://ftp.icdc.zmaw.de/ar5_sea_level_rise/*.

Specifically, in the process of modelling the effects of sea-level rise to year 2100 (case study CS1) it will be assumed that: *i)* no human intervention, such as for example the reconstruction of the dunes system and the build up of artificial barriers, occurs (no action hypothesis); *ii)* the local rates of subsidence will remain constant over time and equal to those currently observed; *iii)* changes in the coast morphology will be only a function of the rates of subsidence (this implies, in particular, that reshaping of the beaches in consequence of morpho-dynamic processes will also be neglected).

In case study CS2, **a coastal storm scenario will be considered, combining the effects of wave and storm surge**. In addition to the three assumptions adopted for CS1, in CS2 it is assumed that *iv)* **the coastal storm conditions** at 2100 are unchanged with respect to the present ones. It is worth to remark that diverging future predictions for the rate of storm surges expected at along the E-R coastal plain have been proposed, based on different analyses. In the framework of the MICORE project[9], and by means of time series analysis, Ciavola et al. (2011) have evidenced a tendency to an increase in the rate of storm surges over time, with an unvaried storminess. Besides, by a different approach based on climate models, Lionello et al. (2012) have predicted a decrease in the storminess.

3.3 Modelling

The modelling is based on a GIS cartographic system exploiting the **Emilia-Romagna region database**. This provides a quick sketch of the apparent effects of the sea-level rise, highlighting those areas where the impacts could be more critical. To describe the land surface, we have made use of a digital terrain model (DTM), incorporating LIDAR (Light Detection and Ranging) renderings and a Digital Vertical Movement Model (DVMM), at various spatial resolutions. A comprehensive summary of the datasets used is gathered in Table 3 and described below.   T3

3.3.1 Case study CS1

In case study CS1, for the determination of the areas with elevation below the mean sea level, the datasets in Table 3 have been merged in a DTM with a 5×5 m planimetric resolution (DTM2012-RER). This has been preferred to a more detailed and complex Digital Surface Model (DSM) that incorporates LIDAR renderings including infrastructures, building and vegetation. Specific tests have been performed, which have confirmed that the former provides more realistic results. The DVMM is the result of the interpolation of data acquired by means of PS-InsSAR[10] (Arpa-RER, 2012). This DVMM has been used to project the expected subsidence at 2100 on a 5×5 m grid. **The expected total vertical displacement at** 2100 **results from the**   Q1.13 **assumption of constant rates of subsidence equal to those currently observed**. The DTM2100 has been obtained adding the total displacement to the DTM2012-RER.

In the framework of CS1, the sea-level variation S to year 2100 is expressed as the combination of three components:

$$S^{CS1}(\omega) = S_{RCP} + S_{GIA} + S_{SUB}(\omega), \tag{1}$$

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[9]See *http://www.micore.eu/*
[10]`goo.gl/OQZE1a`

where $\omega = (\theta, \lambda)$ with θ and λ denoting colatitude and longitude, respectively, S_{RCP} is the contribution according to a specific RCP, S_{GIA} is the GIA contribution, and S_{SUB} accounts for the effects of subsidence. Note that S_{GIA} and S_{RCP} are assumed to be constant for the study area, while S_{SUB} is spatially variable along the E-R coast **(see Figure 2, right frame)**.

Starting from Eq. (1), two different scenarios have been defined. The first, referred to as the **HIGH-END** case scenario, corresponds to the S_{RCP} value associated with RCP8.5 plus 1σ (*i.e.*, 0.57 m). The second, referred to as the **LOW-END** case scenario, is based on RCP2.6 minus its 1σ (*i.e.*, 0.23 m, see Table 2). For both scenarios, the contribution of subsidence is

$$S_{SUB}(\omega) = r_{SUB}(\omega)\Delta t, \tag{2}$$

where $r_{SUB}(\omega)$ represents the rate of subsidence at a given location (in meters per year) and Δt is the elapsed time span in years. Furthermore, according to the IPCC AR5 assessment (see Section 3.1 above), the projected GIA component is

$$S_{GIA} = -0.022 \pm 0.005 \text{ m}. \tag{3}$$

Thus, Eq. (1) gives

$$S_{HE}^{CS1}(\omega) = 0.55 \text{ m} + S_{SUB}(\omega) \tag{4}$$

and

$$S_{LE}^{CS1}(\omega) = 0.21 \text{ m} + S_{SUB}(\omega), \tag{5}$$

for scenarios **HIGH-END and LOW-END,** respectively.

3.3.2   Case study CS2

The objectives of CS2 are *i)* the determination of the potential floodable areas to year 2100 **combining the effects of waves and storm surges** and *ii)* the comparison of these results with the hazard map for the seawater flooding processed in the framework of the FD (European Parliament and Council, 2007). This topic has a crucial impact in the Emilia Romagna region, in view of the continuous loss of natural areas and the strong impact that a possible flooding may have on urban areas and on the tourism infrastructures. This methodology, which follows the approach adopted for CS1, has been based on the modelisation of the future topographic surface and on the simulation of the flooding in consequence of sea-level rise in scenarios **LOW-END and HIGH-END** described above.

To effectively represent the impact of storm surges to year 2100, the sea-level rise $S(\omega)$ predicted by Eqs. (4) and (5) is combined with the **typical S_{STS} rise** associated with characteristic storms in the region, *i.e.,*

$$S_{HE,LE}^{CS2}(\omega) = S_{HE,LE}^{CS1}(\omega) + S_{STS}, \tag{6}$$

where HE and LE denote the HIGH-END and LOW-END scenarios, respectively, and S_{STS} is the total sea water level at the shoreline during **coastal storms, **calculated by combining** the effects of surge, of the astronomical tide and wave set up. For

the S_{STS} component of sea-level change, three scenarios have been adopted in order to process the hazard maps as requested by the FD. Each of them is associated with a different return period: Frequent (10 years return period, P3-FD), Less Frequent (100 years, P2-FD), and Rare ($\gg$ 100 years, P1-FD, see Table 4) (Perini et al., 2012, 2016; Salerno et al., 2012). T4

This study is based on the GIS model **named** `in_CoastFlood`[11] developed by *Servizio Geologico, Sismico, e dei Suoli* Q1.5
5 of Emilia Romagna Region (SGSS-RER) (Perini et al., 2012), which merges the sea surface in the different weather conditions with the land topography (DTM lidar). A damping was applied as a function of the distance from the shoreline, with the exception of those areas which are not directly connected to the sea (Perini et al., 2012; Salerno et al., 2012). Different tests have been applied to validate the model and to choose the most appropriate scenario. This resulted to be P2, the one with a return period of 100 years (a standard in the field of country planning) and characterised by more robust reference values.
10 Scenario P3 was discarded since it affects only a limited portion of the coast, while P1 was discarded because its return period ($\gg$ 100 years) is not clearly defined from a statistical standpoint (Perini et al., 2016).

Once the reference values have been selected (P2-FD), some local tests have been performed to verify if short-term scenarios are worth to be considered, as they are mainly used in urban planning. The tests have confirmed that short-term scenarios (*e.g.,* P2-FD in combination with the pessimistic **HIGH-END** scenario at year 2030) have low significance in terms of change Q2.8
15 of the floodable areas when compared to those reported in map for P3 at present, and as a consequence short-term effects were discarded. Then we used the most detailed DTM available (DTM LIDAR by ENI, 2012) whose resolution (1×1 m) exceeds the one used for CS1. The choice of this different dataset was motivated by its higher resolution, necessary to run the `in_CoastFlood` model. **The model has been used to quantify the change in floodable areas by storm surges at** 2012 **(P2DTM12, present scenario) and** 2100 **(P2DTM2100, future scenario)**.

20 **The importance of high resolution data and models has been also emphasised by Wolff et al. (2016), who first down-** Q2.3
scaled the global DIVA approach to the case study of the E-R coastal plain. As pointed in the Introduction, Wolff et al. (2016) produced a similar work on the E-R costal plain. A comparison with our results below is not straightforward, since their work was mainly aimed at testing the sensitivity of DIVA in such a complex local case study, with attention to the impact on population and potential economical loss. What is relevant to the purpose of our work is their conclusion
25 about the key role of detailed DTM elevation models at to provide realistic assessments at regional scale. In general, previous impacts assessments performed in the same region are based on a methodology that compares water levels to terrain elevation, *i.e.,* the *bath-tub* method. On the contrary, the model employed in this work incorporates the bath-tub method also accounting for the hydrological connectivity between grid cells; only cells directly connected to the sea and with inundated nearby cells are considered flood prone.

30 To optimise **our** computations and for ease of understanding, the simulation has been performed across five distinct areas, **highlighted** in Figure 4. From South to North, the areas range from Cattolica to Rimini (Area 1), from Rimini to Cesenatico F4
(2), from Cesenatico to Fiumi Uniti (3), from Fiumi Uniti to Porto Garibaldi (4), and from Porto Garibaldi to Gorino (5). In Section 5 the results are gathered to provide a comprehensive overview at the full E-R regional scale.

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[11]See *goo.gl/qxVAWY*

4 Results

4.1 Results for CS1

Aim of this Section is to determine those areas whose elevation at 2100 would move from above to below **mean sea level**, by means of realistic estimates of the relative height of the ground. Henceforth we consider the **HIGH-END** scenario, which 5 **implies a** relative sea-level rise of about 55 cm to year 2100.

A first analysis has been performed considering the E-R portion of the Po plain, having an extension of $\sim9,300$ km^2. On this basis, we have computed the variation of land with height above mean sea level by intersecting of DTM2100 with the sea level at 2100, obtained by shifting the present chart datum by $+55$ cm (see Figure 5). As summarised in Table 5, the effect of subsidence **would contribute to the loss of** ~101 **km^2 of land above mean sea level**, whereas considering the combined 10 effect of subsidence and sea-level rise (**HIGH-END** scenario) the extension of the areas below **mean sea level** could reach ~346 km^2. It is apparent **from Figure 5** that the difference is only restricted to the coastal plain and that large discrepancies exist between the N and the S sectors of the E-R coast. For this reason, we opted for a more detailed analysis by splitting the E-R coastal plain, whose total area is $\sim3,043$ km^2, into three sectors that differ for the morphology and for the response to the scenarios, *i.e.*, the Ferrara, Ravenna, and Rimini sectors. Figure 5 shows, in the **HIGH-END** scenario, the extent of the areas 15 that will be located below **mean sea level** to year 2100 (red). In the same Figure, the areas that today are below **mean sea level** are marked in yellow. The largest portion of potentially low land areas to year 2100, is limited to the Ravenna district (right frame in Figure 5). This is in consequence of the high rates of subsidence observed in the area, which is characterised by a low elevation above **mean sea level** (see Table 6). It is important to underline that the submerged areas mostly consist of land not directly connected to the sea ("low land areas" or polders).

Q1.1
Q2.8
F5
T5
Q2.8
Q1.1
Q2.8
Q1.1
Q1.1
Q1.1
T6

20 ### 4.2 Results for CS2

The maps obtained for CS2 (see Figures from 6 to 10) show a large increase in the risk of flooding during coastal storms along the whole E-R coast, in particular in Area 3, from Ravenna to Cesenatico. For the Areas 1 to 5, we now describe in detail the increase of the floodable areas in case of storm surge with respect to the current scenario at 2012 (P2-DTM2012).

4.2.1 Area 1

25 In Area 1 (Figure 6), the effects of subsidence are found to be very small in comparison with other areas; they result in an increase of the floodable area of $+47\%$ with respect to the one predicted by model P2-DTM12. In the **LOW-END and HIGH-END** sea-level scenarios to year 2100, these values increase to $+85\%$ and $+141\%$, respectively. Remarkably, the area mostly affected by the sea-level component **in comparison to subsidence** is the center of the town of Rimini, but also the mouths of the rivers are impacted. In Area 1, the extension of the floodable area is limited to 50-100 m landward with respect to that 30 predicted by P2-DTM12.

F6
Q2.8
Q1.14

4.2.2 Area 2

The results for Area 2 are shown in Figure 7. Compared with other areas, Area 2 is characterised by smaller rates of subsidence,
smaller depressed regions and higher average elevations above the sea level, which naturally mitigates the combined effect of
subsidence and of sea-level rise. The increase of the areas exposed to potential flooding to year 2100 is limited to +65% with
5 respect to present for the only effect of subsidence, while for the **LOW-END and HIGH-END** scenarios we obtain +102% and
+167%, respectively, also including the effects of land subsidence. From the map in Figure 7, **we recognise** that from the N
border to the Uso river mouth, the extension of the area at risk of flooding is dominated by the effects of subsidence. South of
the Uso river mouth, the opposite occurs, with a dominating effect of sea-level rise especially for the **HIGH-END** scenario. We
note that some large portions of urban areas are involved, especially in the municipality of Bellaria-Igea Marina and north of
10 the Rimini harbour.

4.2.3 Area 3

Area 3 (Figure 8) turns out to be the most critical of the E-R coast in consequence of the high rate of subsidence that char-
acterises its northern portion, between Fiumi Uniti and Cervia. Here we observe the most significant increase (+248%) for
the floodable area to year 2100 with respect to 2012 (P2-DTM12), as a consequence of current subsidence rates. When the
15 expected sea-level rise is also taken into consideration, the increase rises up to +308% and to +404% for the **LOW-END and
the HIGH-END** scenarios, respectively. These values evidence that the effect of the sea-level rise is marginal with respect to
subsidence, at least for scenario **LOW-END**. However, it should be remarked that also in this area the effect of the storm surge
would flood the entire coast with a frontal ingression that could extend several hundred meters, exceeding up to 0.5 km the
present scenarios, involving large urban areas.

20 ### 4.2.4 Area 4

In Area 4 (Figure 9), the scenarios predicted to year 2100 are sharpened by the presence of wide low-elevation regions, with
some of them currently below the mean sea level. This is exacerbated by two factors. The first is the total absence of natural
or artificial defences such as dunes and embankments that could counteract the marine action. The second is the high rate of
subsidence, reaching 15 and even 20 mm yr^{-1} at some locations like Porto Corsini, Lido Adriano and Lido di Dante. The
25 increase of the floodable area, only in consequence of the subsidence, would be of ∼153% relative to P2-DTM12. This rises
to +214% and +294% when the predicted sea-level rise at 2100 is taken into account, according to the **LOW-END and HIGH-
END** scenarios, respectively. In this model, the ingression would occur along the whole coast, involving urban areas as well as
natural reserves. The expected inner limit for the areas reached by the flooding would move inland by about 1 km with respect
to P2-DTM12. Furthermore, in case of flooding no natural barriers are present. We should remark, however, that the recent
30 assessment by Arpa-RER (2012) for the subsidence in this area has revealed a strong decrease to values of 6-7 mm yr^{-1}. This
suggests that these proposed scenarios could be revised in the near future, and possibly replaced by more optimistic ones.

4.2.5 Area 5

The results for Area 5, shown in the map of Figure 10, indicate an increase of ∼59% of the floodable area in case of storm F10
surge with return period of 100 years (P2 in Table 4), when only the effects from land subsidence are considered (see green
coloured areas). This result is crucial, since currently in the Po Delta area the subsidence is assumed almost completely natural
5 (Teatini et al., 2011b), with rates that locally reach 11 mm yr^{-1}. Accordingly, it appears unlikely to expect a reduction, neither
natural nor induced, in the next 100 years. If we include the effect of the predicted sea-level rise at 2100, the percent increase
of the floodable areas rises to 102% and 214% for the **LOW-END** and **HIGH-END** scenarios, respectively (yellow and red Q2.8
areas). It should be remarked that a large portion of those areas that will become floodable at 2100 are currently protected by
embankments. The above estimates imply that the current artificial defenses would loose their functionality at 2100. Further
10 considerations relate with the inward displacement of more than 2 km of the floodable area boundaries relative to the P2-
DTM12 predictions. This would in fact largely involve urbanised areas although the propagation inward of the sea would be
localised at weak or low points along the embankments. As a consequence, a constant and efficient maintenance is required for
the embankments to counteract the effects of subsidence and of future storm surges.

4.3 A regional synthesis for CS2

15 Based on the analysis above, the combined effect of subsidence and sea-level rise in terms of increase of the floodable areas
at 2100 can be summarised as follows (see Table 7). *i)* Land subsidence plays a non negligible role, leading to an increase of T7
the floodable areas of ∼95% with respect to that predicted by P2-DTM12 along the entire E-R coastal plain to year 2100; ***ii)***
the superimposition of the **HIGH-END** scenario for sea level would enlarge the extension of the floodable areas in case of P2 Q2.8
event by more than three times (+236%) with respect to P2-DTM12; ***iii)*** the most critical portion of the E-R coast in terms of
20 increase in the floodable area is recognised as the central one, corresponding to Areas 3 and 4; in this respect Area 1 turns out
to be the less critical; ***iv)*** in the E-R coast portion that extends between Casal Borsetti and Cervia (Areas 3 and 4), the increase
is dominated by subsidence which tapers the effect related to sea-level rise. *v)* To the North, areas where subsidence dominates
are alternated with those in which sea-level has a major role. Those are mainly localised where defences are in place but gaps
are present.

25   For a correct interpretation of our results, it should be remarked that in CS1 we have only considered the combined effect of
subsidence and sea-level rise while in CS2 we have also included the effects of storm surges. In both cases, we are omitting the
effects of the coastal morfodynamics and of the solid transport by the sea and by the rivers, as well as the anthropogenic factors
that could concur in modifying the landscape by the end of the century. **These, in some cases,** could contribute to mitigate the
effects of the predicted sea ingression.

5 Discussion

Our study relies upon a a number of important assumptions, regarding: the role and the rate of land subsidence, the morphological conditions, and the adopted sea-level projections. Each of these assumptions implies some uncertainties, which required some further discussion.

The surmise of a linear trend of subsidence can be motivated observing that the major temporal variations in the rates are observed in confined areas, where groundwater exploitation and anthropic impact are particularly strong (for various specific case studies, see for example Le Mouélic et al., 2005; Wang et al., 2012; Raucoules et al., 2013). In the remaining parts of the E-R coastal plain, which cover most of the study area, the subsidence rates measured during the different monitoring campaigns are comparable. We interpret this spatial and temporal distribution as a constant background signal, likely due to natural subsidence, with overlapping local perturbations due to human activity. These are difficult to model because of the large number of variables and the complexity of the driving processes. In addition, measures imposed by the the Emilia-Romagna Regional Administration over the last 30 years to reduce the fluids extraction have allowed a progressive stabilization of subsidence rates in most of these critical areas. Thus, assuming that the measures will be maintained, future rates of subsidence will not be likely to exceed the current ones. Current subsidence rates were then used in modelling as they well describe the geodynamic condition of the Emilia-Romagna coast at regional scale, pointing out the present state of the highly subsiding areas. It is implied that the results in Table 5 implicitly reflect the benefits of the ongoing adaptation strategy consisting in mitigating subsidence through reduced fluid extractions.

Regarding the morphological changes, it was chosen to consider a rigid substrate modified only by the subsidence (translation), since, at present, it has not been possible to apply a dynamic modelling approach integrating also long term coastal evolution (e.g. beach changes) at the regional scale, or land use projection. In this view, the model excludes the natural adaptation of the coastal system as well as it funds on the assumption of "no intervention" by man (no nourishment, no upgrading in coastal defense systems, etc.).

Another important source of uncertainty arises from the sea-level projections along the E-R coastal plain. In this work, we have relied upon projections based on global scenarios reported in the IPCC AR5 (Church et al., 2013), and corresponding to specific RCPs. However, recent ensemble simulations from Adloff et al. (2015) have shown that projections within the Mediterranean Sea are particularly sensitive to the conditions assumed in the near-by Atlantic region, which is uncertain in the general circulation models. According to Slangen et al. (2017), the minimum uncertainty associated with the sea-level projections to year 2100 is $\pm \sim 10$ cm, which is comparable with the uncertainty associated to our projections in Table 2, for all the possible RCPs. This enlightens the need, in future studies about the impacts of sea-level rise along the E-R coastal plain, of high quality regional ocean models.

6 Conclusions

In this work we have performed a GIS analysis aimed at **identifying** those areas of the E-R coastal plain that would suffer, by the end of this century, from an increased vulnerability in response to land subsidence and sea-level rise. These will cause the loss of large portions of emerged land, in particular, beaches, wetlands and dunes. While the first would have a relevant impact on the tourism industry of the region, wetlands and dunes would threaten valuable ecosystems, essential for the preservation of nature and of life. A second major effect would be the enlargement of the portions of land exposed to water flooding in case of storm surges.

The effects of sea-level rise have been modelled in terms of land loss and increase of floodable areas, assuming storm surges with a return period of 100 years. The distribution of floodable areas has been compared with current scenarios designed by the Emilia-Romagna authority in the framework of the DLGS 49/2010, national emanation of the Flood Directive (EU 2007/60). The high quality of the data sets employed both at regional and local scale and their enhanced spatial resolution have allowed for a detailed analysis, with a focus on the effect of the single components. The eustatic effect coupled with subsidence has, in the context of the E-R plain, a relevant long-term impact, although in different ways along the coast. The subsidence appears to be the most significant cause in some areas, such a the Ravenna district. The combination of a 55 cm increase in sea level (**HIGH-END** scenario, based on the IPCC AR5 projections) with a widespread subsidence that is expected to affect with different rates the entire coastal area, results in an increase of about 346 km^2 of the land **that could be partly below mean sea level**. The new areas below **mean sea level** could be directly connected to the sea and therefore potentially floodable. This would lead to an increase of the former wetlands reclaimed at the beginning of the last century.

In a step forward, we have combined the above results for the **LOW-END (**$+23$** cm) and HIGH-END (**$+55$ cm) sea-level scenarios with the predicted effects of **effects of coastal storm phenomena**, *i.e.* **total sea water level, based on the model "in_CoastFlood" with scenarios** with return period of 100 years. The results have evidenced that: *i)* subsidence and storm surges would lead to an increase from 29 to 59 km^2 of floodable areas at 2100; *ii)* when subsidence and storm surges are combined with sea-level rise, the increase of floodable areas is $+133$ and $+236\%$ for the **LOW-END and HIGH-END** scenarios, respectively. In our study, we did not consider possible changes in the current observed rates of subsidence **and storminess**, nor any human intervention to adapt the existing coastal defence to the evolving shape of the coastline. This work, indeed, discusses the scenario of maximum vulnerability for the case of "no intervention", with the aim of defining the most appropriate actions to be applied in the updating of the FD plan, expected for year 2021.

Integrating the above results with the flooding maps produced in the framework of the DGLS 49/2010, it has been possible to compare the current situation with possible future scenarios. The methodology implemented, which demands relatively limited computational resources, will allow new analyses and further maps to plan new possible mitigation actions as well. This would leave however the Emilia-Romagna coastal plain exposed to a certain level of risk, in consequence of its natural shape and geology. **We expect that the output of our analysis will support the planned activities for the second stage of the Flood Directive** 2007/60**, *i.e.* the updating of the knowledge framework and hazard and risk maps by** 2019**. These should include, in fact, the risks assessment driven by the climate change, which was not presented in the first cycle of**

the directive application, in order to identify mitigation and adaptation measures. Likewise, we expect that this work can provide an important contribution to the working group on the Regional Climate Change Strategy, which aims to develop an action plan by 2018. In this respect, this work can be considered the starting point for decision makers as well as for the scientific community to define the areas exposed to a major risk, the possible actions to mitigate the predicted risks, and the strategies to handle the forthcoming strong surges and flooding.

7 Code availability

The codes **employed on this work** may be available on request from LP.

8 Data availability

The data **employed on this work** may be available on request from LP.

Author contributions. **The work presented here was carried out in collaboration between all authors. LP, LC and PL defined the research theme and designed most of the methods and experiments. MO, GG and GS have designed some of the methods and experiments and have contributed to the interpretation of the results. All authors have contributed to write the paper. All authors have contributed to, seen and approved the manuscript.**

Competing interests. The authors declare no competing interests

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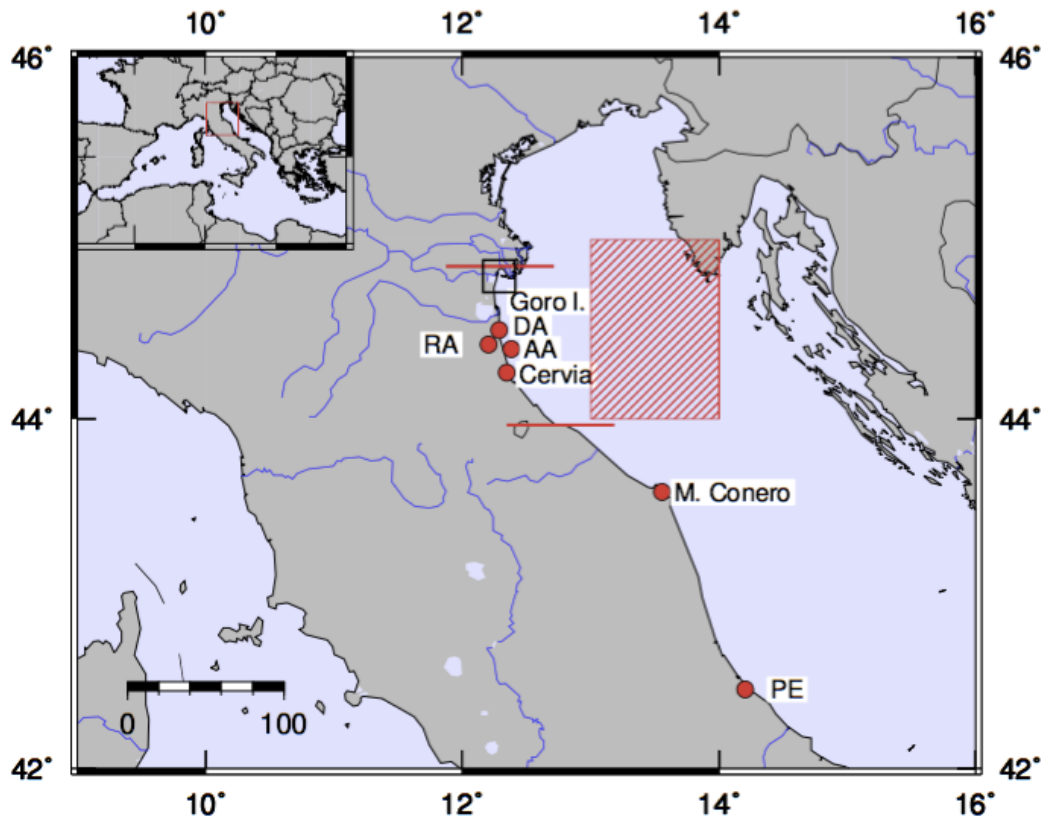
Figure 1. Map of the Northern Adriatic Sea and of the surroundings. Horizontal ticks on the East coast of Italy mark the northern and southern limits of the E-R shoreline. The hatched rectangle shows the cell of the IPCC AR5 discretisation of the global oceans used to represent the projected sea-level change in front of the E-R coast (RA: Ravenna, AA: Angela-Angelina gas field, PE: Pescara). The town of Cervia divides E-R coast into two sectors, referenced to as North (N) and South (S) in the body of the paper.
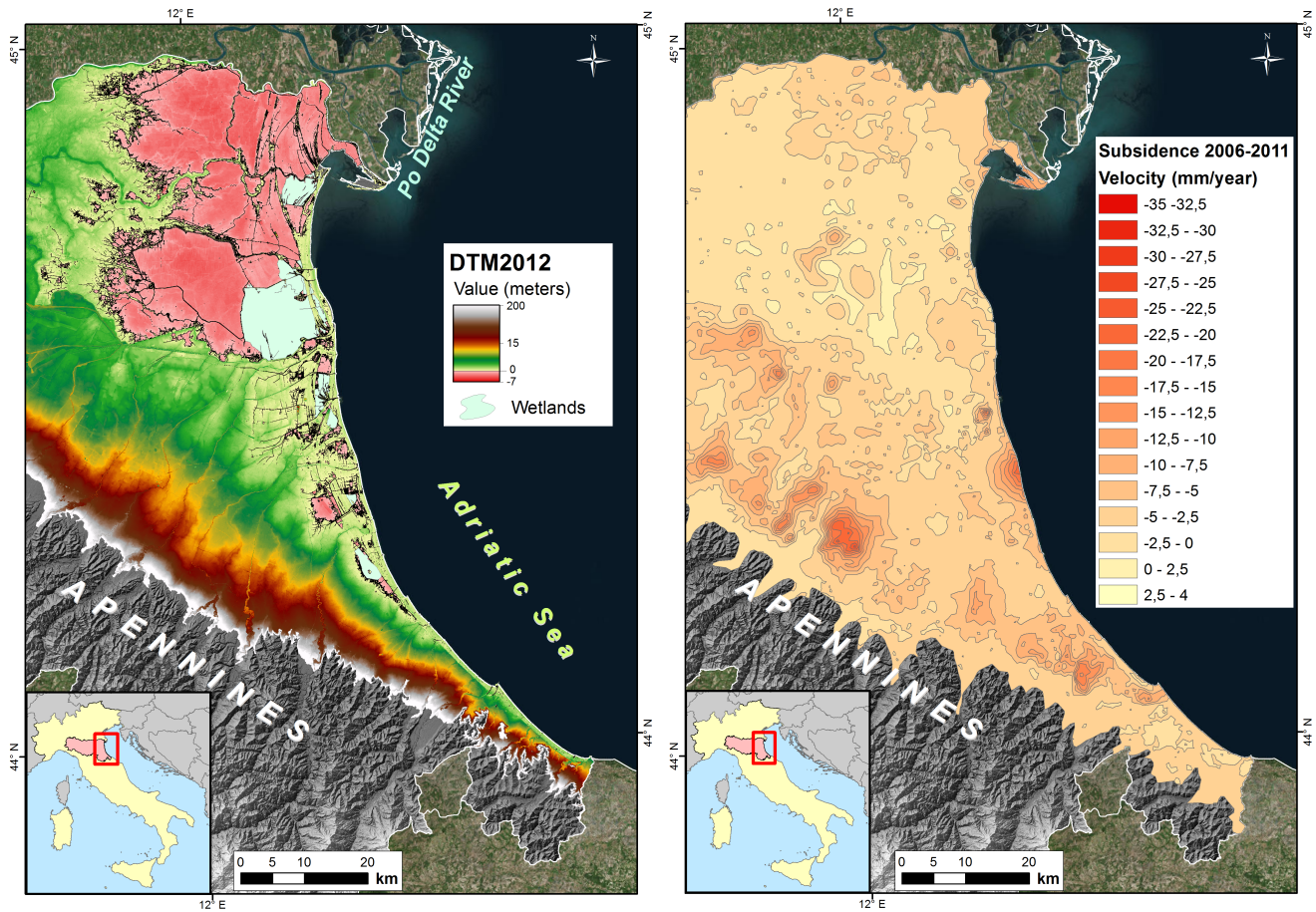
Figure 2. Left: the altimetry and morphology of the E-R coastal plain resulting from a high resolution Digital Terrain Model (DTM). The reference height in the map is the zero of the Italian geodetic network. The remarkable difference between the N and the S sectors in term of the extension of low lands is evident. **Right:** Subsidence rate map of the E-R coastal plain according to the InSAR monitoring for the time period 2006-2011 **(Arpa-RER, 2012) [Q1.17].**
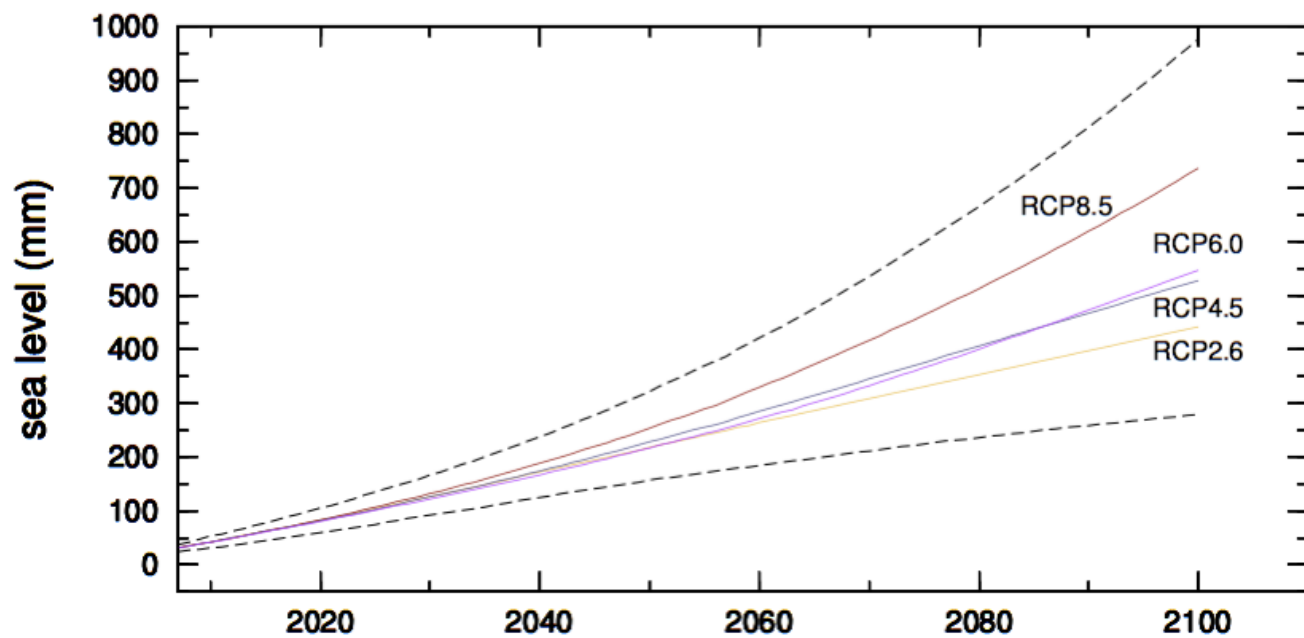
Figure 3. Sea-level pathways according to IPCC AR5. Dashed lines show the lower and the upper limits of the projections, corresponding to the upper limit of RCP 8.5 and to the lower limit of the RCP 2.6. Projections are referred to the average sea-level values in the period 1986-2005.
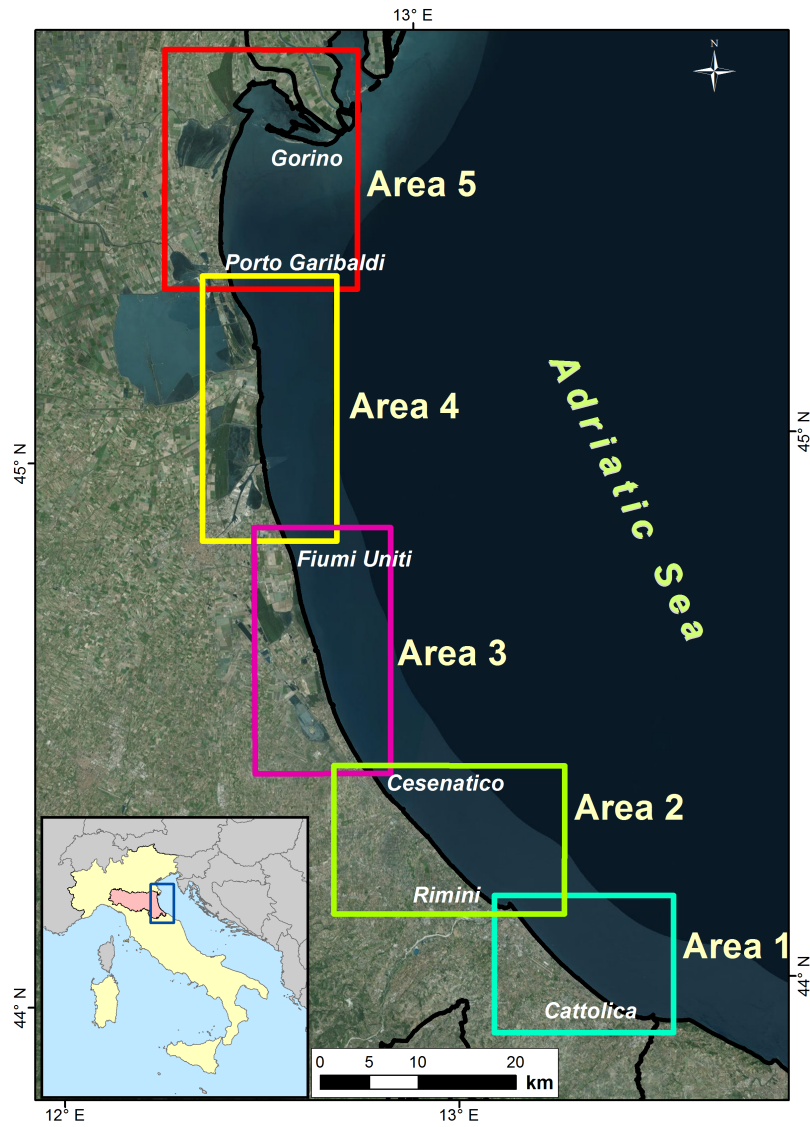
Figure 4. Location and boundaries of the five areas (Area 1 to Area 5) on which the E-R coastal plane has been divided.
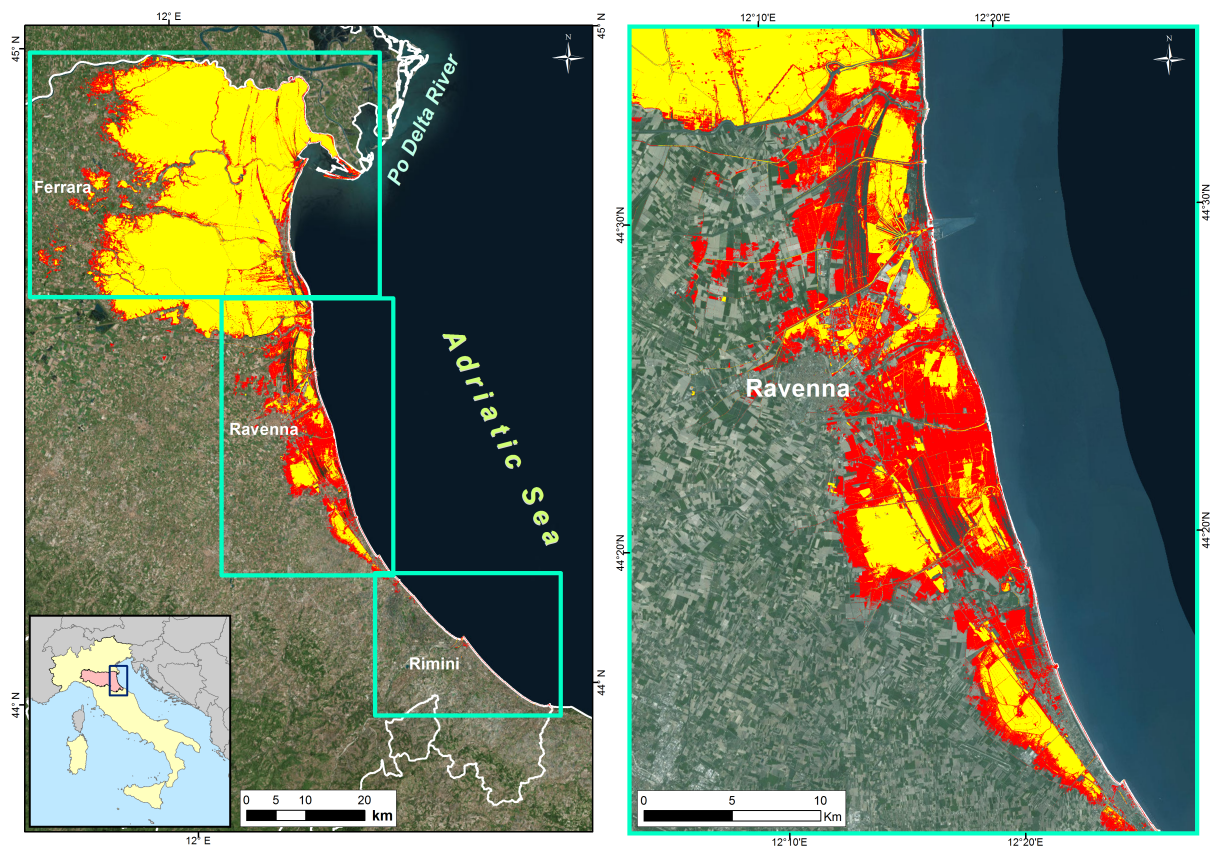
Figure 5. Results for the simulations in CS1, at the E-R coastal plain scale (left) and for the area of Ravenna (right). Lands that are currently located below sea level are evidenced in yellow. New areas predicted to be located below sea level at 2100 are marked in red.
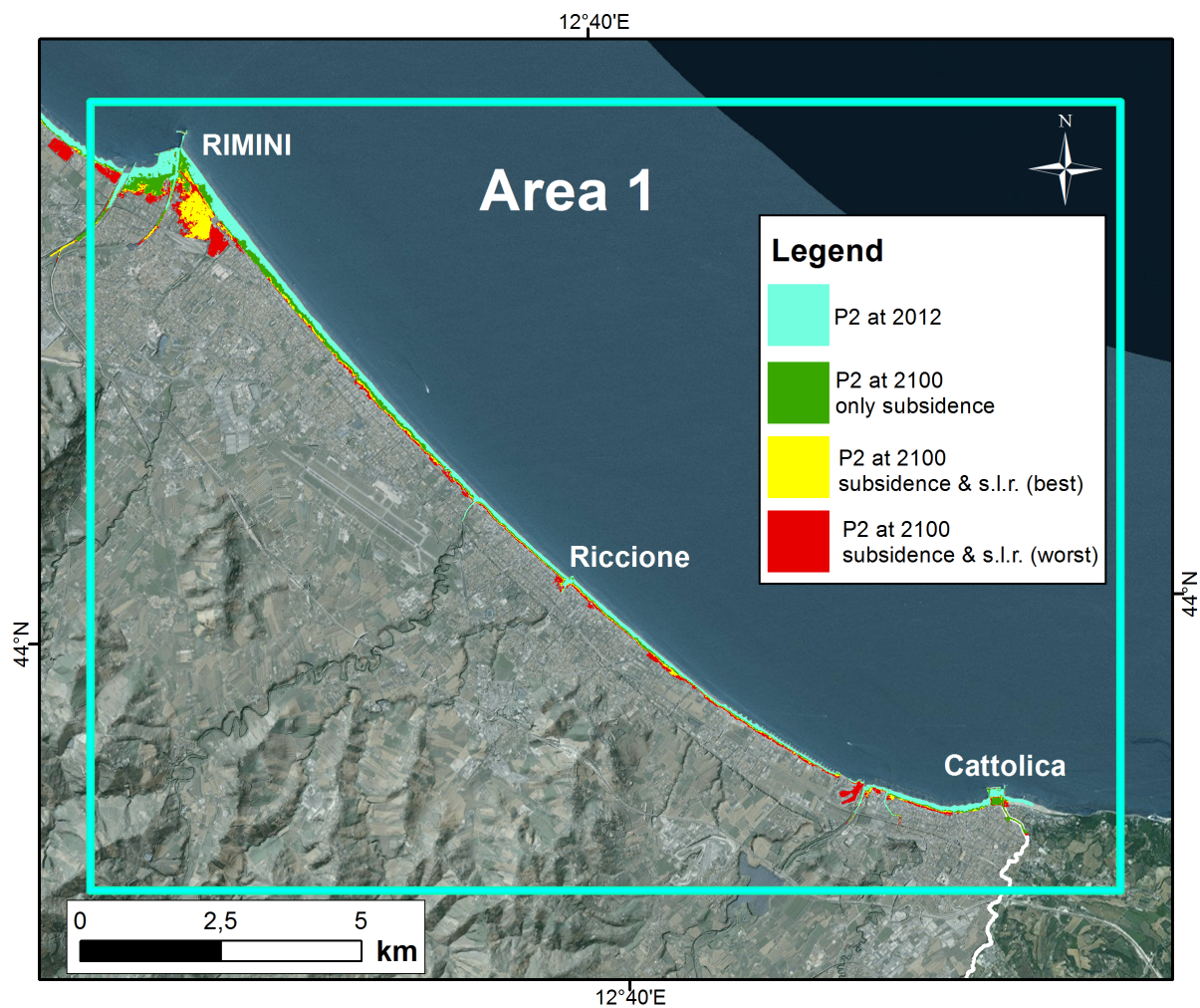
Figure 6. Floodable regions across Area 1 in case of storm surge for case P2 at 2100. The assumptions in modelling are color-coded in the inset. **In [Q2.8] Figures 6-10 "best" and "worst" refer to the LOW-END and HIGH-END scenarios described in the body of the paper, respectively**

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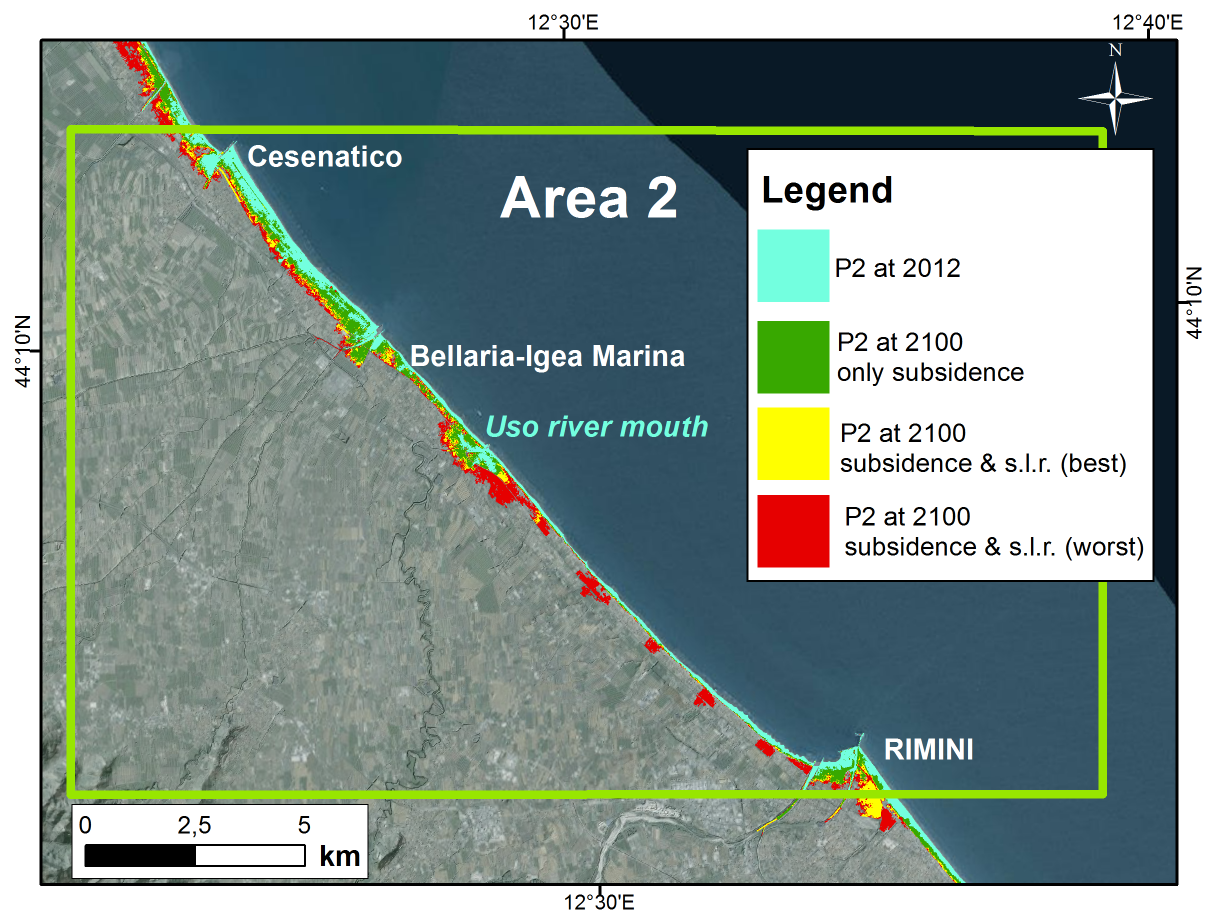
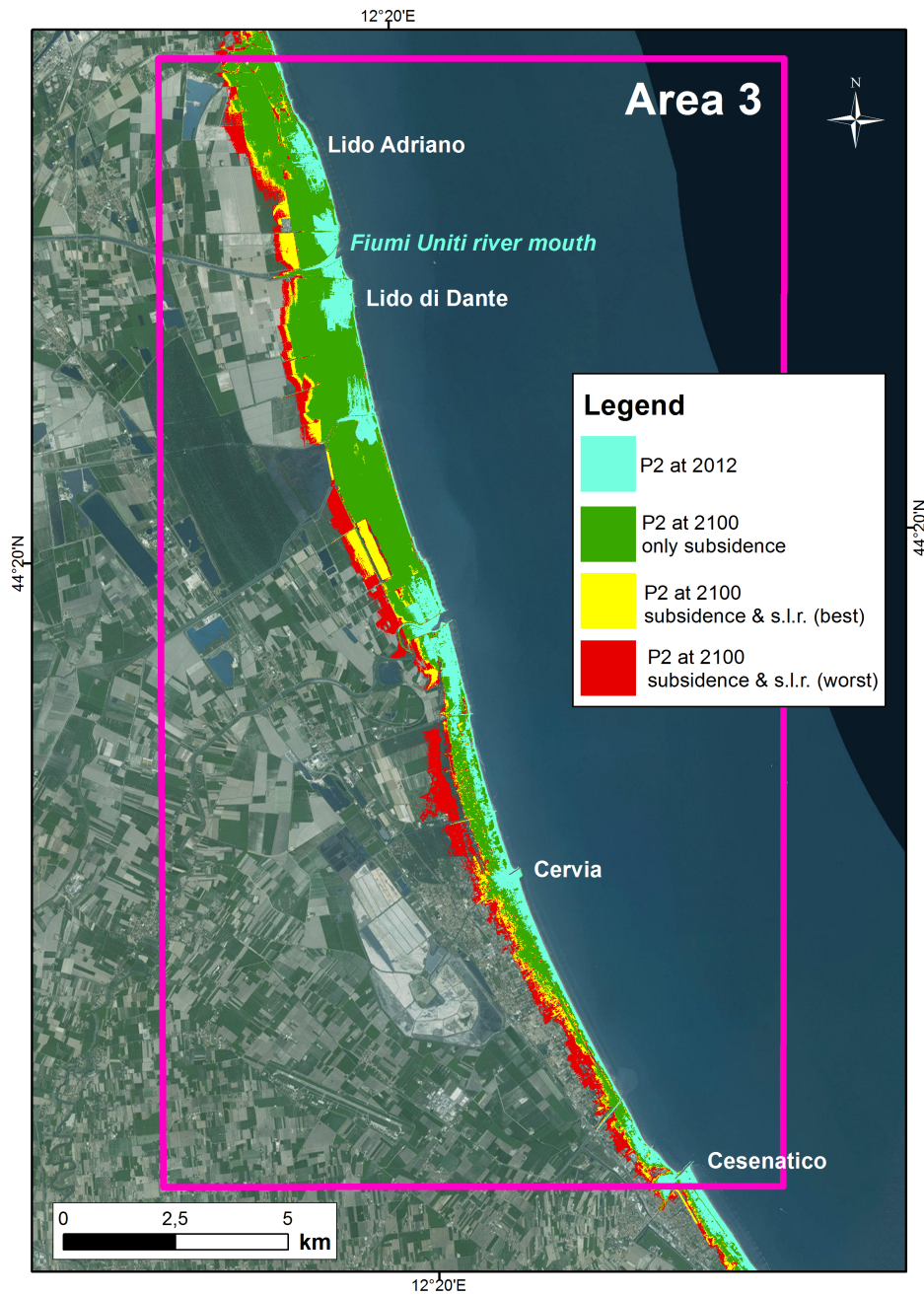**Figure 7.** The same as in Figure 6, but for Area 2.

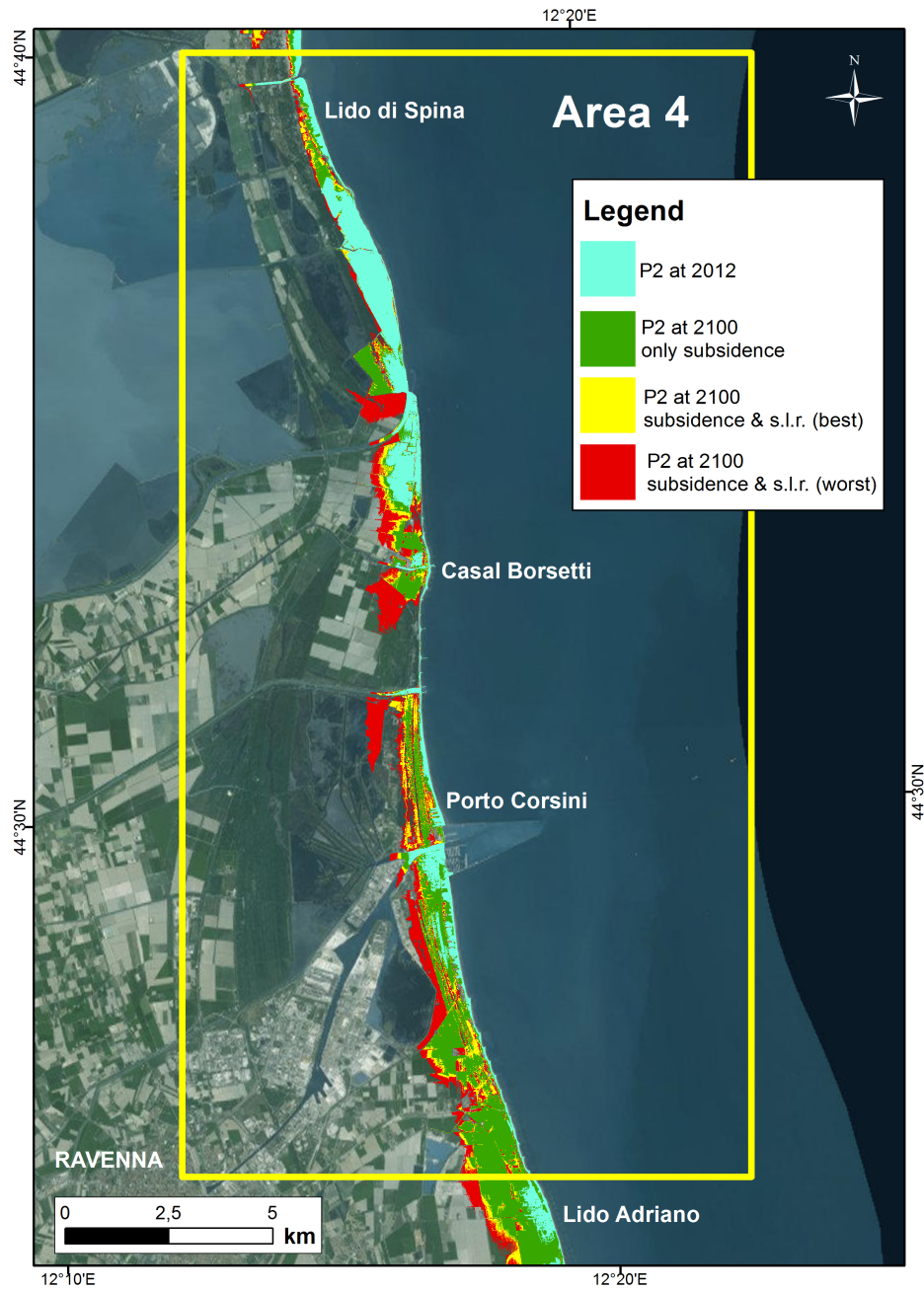**Figure 8.** The same as in Figure 6, but for Area 3.

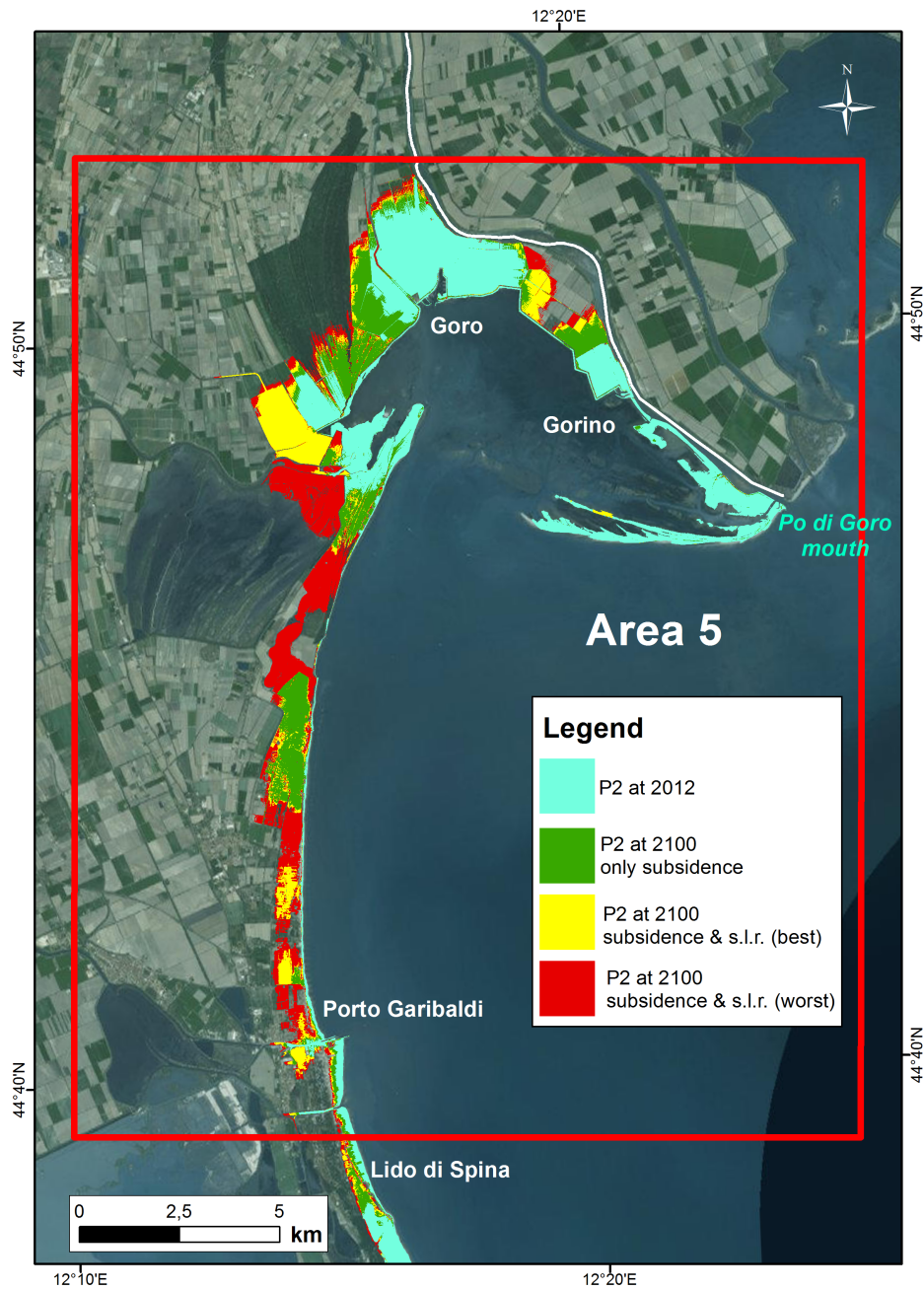**Figure 9.** The same as in Figure 6, but for Area 4.

Figure 10. The same as in Figure 6, but for Area 5.

Table 1. Summary of the physical characteristics of the E-R coast. The N and S sectors are defined in Figure 1.

	North sector (N)	South sector (S)
Coastal plain width (D)	$5 < D < 40$ km (from South to North)	$0.8 < D < 5$ km (from South to North)
Dominant elevation above sea level (H)	$-1 < H < 1$ m	$0 < H < 3$ m
Dry beach width (D_s)	$0 < D_s < 300$ m, mean value $\overline{D}_s = 60$ m	$10 < D_s < 180$ m, mean value $\overline{D}_s = 80$ m
Geomorphological features	Beach ridges, dunes, lagoons, wetlands, reclaimed areas, sand spits	Beach ridges, dunes (only towards the north), saltpans
Shape of the shoreline	Wavy, convexities at river estuaries, more complex at river spits	Straight with asymmetric wedges at Cesenatico and Rimini harbors
Backshore land use	Urbanized areas, agriculture, vegetation and wetlands	Wide urbanized areas, agriculture and vegetation
Medium/long term tendency	Variable, tending to rectify	Stable, with local changes

Table 2. Sea level predicted during the time interval 2081-2100 with respect to 1986-2005, according to the four IPCC AR5 RCPs. The Adriatic and Mediterranean values are averaged values across these seas. These projections do not include the GIA component of sea-level change.

RCP	E-R coast	Adriatic	Mediterranean	Global
	m	m	m	m
2.6	0.30 ± 0.07	0.31 ± 0.01	0.36 ± 0.02	0.38 ± 0.15
4.5	0.34 ± 0.09	0.37 ± 0.01	0.42 ± 0.03	0.45 ± 0.16
6.0	0.33 ± 0.08	0.36 ± 0.02	0.42 ± 0.03	0.47 ± 0.16
8.5	0.45 ± 0.12	0.48 ± 0.02	0.57 ± 0.03	0.60 ± 0.19

Table 3. Description of the four input models employed for the definition of case studies CS1 and of CS2.

Input dataset name	Interpolated points	Altimetric tolerance	Output dataset name	Grid size
LIDAR 2008 PNT	2 p/m^2	±15 cm	DTM 2008 PNT	2×2 m
LIDAR 2010 RER	4 p/m^2	±10 cm	DTM 2010 RER	1×1 m
LIDAR 2012 ENI	4 p/m^2	±10 cm	DTM 2012 ENI	1×1 m
PS-InSAR 2006-2011 PNT	1 p/26 m^2	± 2 mm	DVMM	5×5 m

Table 4. Expected sea-level rise in the occurrence of different type of characteristic storm surges and their expected return period (Perini et al., 2012, 2016; Salerno et al., 2012).

Type of surge	Return period	Sea surface elevation
	years	m
Frequent (P3)	10	1.49
Less Frequent (P2)	100	1.81
Rare (P1)	$\gg$ 100 **[Q1.19]**	2.50

Table 5. Areas expected to be above and below mean sea level (m.s.l.) to year 2100, compared to year 2012. Upperscript [a] denotes only subsidence; [b] includes subsidence and sea-level rise.

Year	Above m.s.l.	Below m.s.l.	Lost area above m.s.l.
	km^2	km^2	km^2
2012	8083.8	1216.4	
2100 [a]	7982.5	1318.3	101
2100 [b]	7737.6	1563.2	346

Table 6. Detail of the future areas below sea level, compared to year 2012.

Area	at 2012 km^2	at 2100 km^2	Difference km^2
Ferrara	1143.32	1331.41	188.09
Ravenna	72.00	224.28	152.28
Rimini	0.72	6.34	5.61

Table 7. Regional floodable areas in case of storm surges for case P2 described in Table 4. The increase in amount of flooded area is relative to P2-DTM12. Upperscript [a] denotes only subsidence, [b] includes subsidence and sea-level rise (LOW-END **[Q2.8]** scenario), [c] includes subsidence and sea-level rise (HIGH-END **[Q2.8]** scenario).

Case	Flooded area km^2	Increase %
P2-DTM12	29	
2100 [a]	59	95
2100 [b]	72	133
2100 [c]	105	236