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Cost-benefit analysis of coastal flood defence measures in the North Adriatic Sea

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Abstract

The combined effect of global sea level rise and local subsidence phenomena poses a major threat to coastal settlements. Flooding events are expected to grow in frequency and magnitude, increasing the potential economic losses and costs of adaptation. In Italy, a large share of the population and economic activities are located along the coast of the peninsula, although risk of inundation is not uniformly distributed. The low-lying coastal plain of Northeast Italy is the most sensitive to relative sea level changes. Over the last half a century, the entire north-eastern Italian coast has experienced a significant rise in relative sea level, the main component of which was land subsidence. In the forthcoming decades, sea level rise is expected to become the first driver of coastal inundation hazard. We propose an assessment of flood hazard and risk linked with extreme sea level scenarios, both under historical conditions and sea level rise projections at 2050 and 2100. We run a hydrodynamic inundation model on two pilot sites located in the North Adriatic Sea along the Emilia-Romagna coast: Rimini and Cesenatico. Here, we compare alternative risk scenarios accounting for the effect of planned and hypothetical seaside renovation projects against the historical baseline. We apply a flood damage model developed for Italy to estimate the potential economic damage linked to flood scenarios and we calculate the change in expected annual damage according to changes in the relative sea level. Finally, damage reduction benefits are evaluated by means of cost-benefit analysis. Results suggest an overall profitability of the investigated projects over time, with increasing benefits due to increased probability of intense flooding in the next future.

Key-words: coastal inundation Italy extreme sea level rise

Abbreviations: MSL (Mean Sea Level); TWL (Total Water Level); ESL (Extreme Sea Level); SLR (Sea Level Rise); VLM (Vertical Land Movements); DTM (Digital Terrain Model); EAD (Expected Annual Damage)

1. Introduction

Globally, more than 700 million people live in low-lying coastal areas (McGranahan et al. 2007), and about 13% of them are exposed to a 100-year return period flood event (Muis et al. 2016). On average, one million people located in coastal areas are flooded every year (Hinkel et al. 2014). Coastal flood risk shows an increasing trend in many places due to socio-economic growth (Bouwer 2011; Jongman et al. 2012b) and land subsidence (Syvitski et al. 2009; Nicholls and Cazenave 2010), but in the near future sea level rise (SLR) will likely be the most important driver of increased coastal inundation risk (Hallegatte et al. 2013; Hinkel et al. 2014). Evidences show that global sea level has risen at faster rates in the past two centuries compared to the millennial trend (Kemp et al. 2011; Church and White 2011), topping 3.2 mm per year in the last decades mainly due to ocean thermal expansion and glacier melting processes (Mitchum et al. 2010; Meyssignac and Cazenave 2012). According to the IPCC projections, it is very likely that, by the end of the 21st century, the SLR rate will exceed that observed in the period 1971-2010 for all Representative Concentration Pathway (RCP) scenarios (IPCC 2019); yet the local sea level can have a strong regional variability, with some places

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experiencing significant deviations from the global mean change (Stocker et al. 2013). This is particularly worrisome in regions where changes in the mean sea level (MSL) are more pronounced, considering that even small increases of MSL can drastically change the frequency of extreme sea level (ESL) events, leading up to situations where a 100-year event may occur several times per year by 2100 (Carbognin et al. 2009, 2010; Vousdoukas et al. 2017, 2018; Kirezci et al. 2020). Changes in the frequency of extreme events are likely to make existing coastal protection inadequate in many places, causing a large part of the European coasts to be exposed to flood hazard. Under these premises, coastal floods threaten to trigger devastating impacts on human settlements and activities (Lowe et al. 2001; McInnes et al. 2003; Vousdoukas et al. 2017). In this context, successful coastal risk mitigation and adaptation actions require accurate and detailed information about the characterisation of coastal flood hazard and the performance of alternative coastal defence options. Cost-benefit analysis (CBA) is widely used to evaluate the economic desirability of a DRR project (Jonkman et al. 2004; Mechler 2016; Price 2018). CBA helps decision-makers in evaluating the efficacy of different adaptation options (Kind 2014; Bos and Zwaneveld 2017).

In this study, designed coastal renovation projects in the municipalities of Rimini and Cesenatico, in Italy, are compared against the baseline scenario in terms of net benefits under changing climate conditions. First, we employ the 2D-hydrodynamic ANUGA model (Roberts et al. 2015) for simulating coastal inundation scenarios associated with ESL projections over the two pilot areas located along the Emilia-Romagna coast (North Adriatic Sea). Flood hazard maps are produced for current conditions (2020) and future conditions (2050 and 2100) by combining the local data from historical ESL events with the estimates of relative mean sea level (RMSL) change for those locations. RMSL change accounts for both the eustatic global rise and the locally-measured land vertical movement effect. Each inundation scenario simulated by the model is translated in terms of direct economic impacts using a locally-calibrated damage model. The combination of different risk scenarios in a CBA framework allows to estimate the economic benefits brought by the project implementation in terms of avoided direct flood losses up to the end of the century.

2. Area of study

Located in the central Mediterranean Sea, the Italian peninsula has more than 7,500 km of coasts, hosting around 18% of the country population (ISTAT), numerous towns and cities, industrial plants, commercial harbours and touristic activities, as well as cultural and natural heritage sites. Existing country-scale estimates of SLR up to the end of this century helps to identify the most critically exposed coastal areas of Italy (Lambeck et al. 2011; Bonaduce et al. 2016; Antonioli et al. 2017; Marsico et al. 2017). The North Adriatic coastal plain is acknowledged to be the largest and most vulnerable location to extreme coastal events due to the shape, morphology and low bathymetry of the Adriatic sea basin, which cause water level to increase relatively fast during coastal storms (Carbognin et al. 2010; Ciavola and Coco 2017; Perini et al. 2017). The ESL here is driven mainly by astronomical tide, ranging about one meter in the *northernmost* sector, and meteorological forcing, such as low pressure, seiches and prolonged rotational wind systems, which are the main trigger of storm surge in the Adriatic basin (Carbognin et al. 2010; Vousdoukas et al. 2017). 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. We focus our analysis on two pilot sites located along the Adriatic coast of Emilia-Romagna, shown in figure 1: Cesenatico and Rimini.

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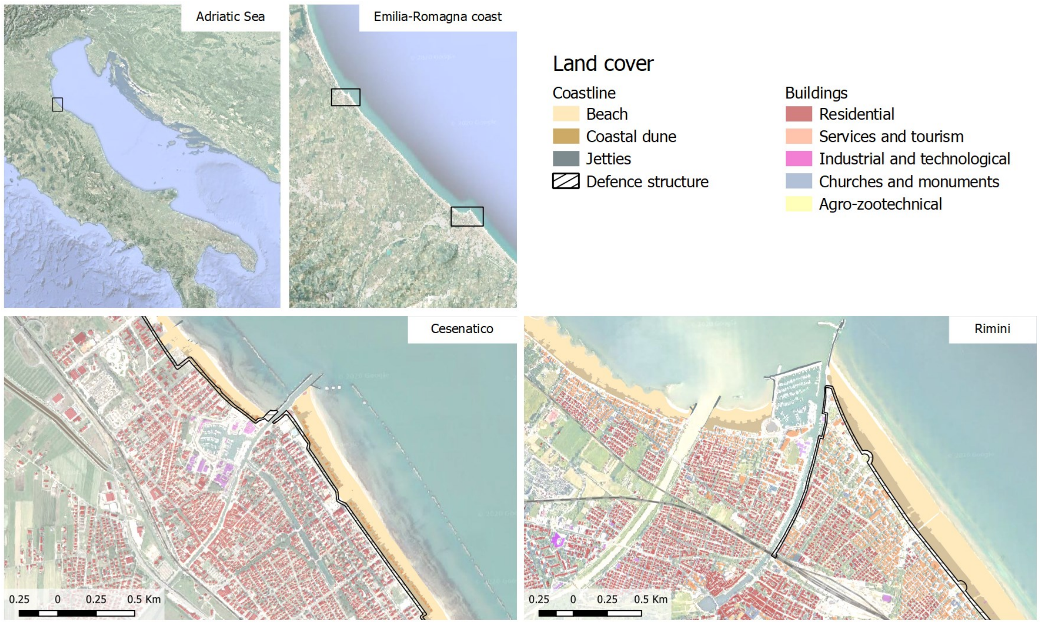

Figure 1. Pilot areas locations along the Emilia-Romagna coast: Cesenatico and Rimini. The coastal defence structure assessed in this study are shown in black. Buildings footprint data from Regional Environmental Agency (ARPA) 2020. Basemap © Google Maps 2020.

The number of annual ESL events reported 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. The landscape along the 130 km regional coastline is almost flat, the only relief being old beach ridges, artificial embankments and a small number of dunes. The coastal perimeter is delineated by a wide sandy beach that is generally protected by offshore breakwaters, groins and jetties. The land elevation is often close to (or even below) the MSL, while the coastal corridor is heavily urbanised. Cesenatico has about 26,000 residents, while Rimini has 150,000. These port towns have a strong touristic vocation, hosting large beach resort and bathing facilities along the beach and hundreds of hotels and rental housing located just behind the seaside. Both towns are affected by beach erosion and the regression of the coastline, and on several occasions they suffered from coastal storms resulting in flooding of buildings and activities. In some cases, the storm surge obstructed the river outlets causing the overflow of channels and the flooding of surrounding areas (Perini et al. 2011).

3. Methodology

3.1 Components of the analysis

Coastal inundation phenomena are caused by an increase of total water level (TWL), most often associated to extreme sea level (ESL) events, which are generated by a combination of high astronomical tide and meteorological drivers such as storm surge and wind waves (figure **2**). Estimates of ESL are obtained for the North Adriatic up to year 2100 by combining reference hazard scenarios derived from historical records with regionalised projections of SLR (Vousdoukas et al. 2017) and local vertical land movements (VLM) rates. Four ESL frequency scenarios, namely once in 1, 10, 100- and 250-years, are considered. The hydrodynamic model ANUGA is applied to simulate the inundation of land areas during ESL accounting for individual components

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(storm surge, tides and waves). Land morphology and exposure of coastal settlements are described by high-resolution DTM and bathymetry, in combination with land use and buildings footprints. The effect of hazard mitigation structures (both designed and under construction) are explicitly accounted in the "defended" simulation scenario, in contrast to the baseline scenario, where only existing defence structures (groins, jetties, breakwaters and sand dunes) are accounted.

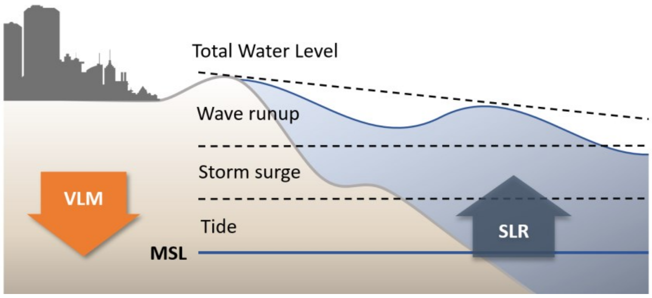

Figure 2. Components of the analysis for extreme sea level events: total water level is calculated as the sum of tide, storm surge and wave runup over mean sea level. Vertical land movement and eustatic sea level rise affects the mean sea level on the long run.

3.2 Vertical Land Movement

Vertical land movements result from a combination of slow geological processes such as tectonic activity and glacial isostatic adjustment (Peltier 2004; Peltier et al. 2015), and medium-term phenomena, such as sediment loading and soil compaction (Carminati and Martinelli 2002; Lambeck and Purcell 2005). The latter can greatly oversize geological processes at local scale (Wöppelmann and Marcos 2012); in particular, faster subsidence occurs in presence of intense anthropogenic activities such as water withdrawal and natural gas extraction (Teatini et al. 2006; Polcari et al. 2018). Most of the peninsula shows a slow subsiding trend, although with some local variability. An estimate of VLM rates due to tectonic activity have been derived from studies conducted in Italy (Lambeck et al. 2011; Antonioli et al. 2017; Marsico et al. 2017; Solari et al. 2018). The North Adriatic coastal plain shows the most intense long-term geological subsidence rates (about 1 mm per year), increasing North to South. Yet in the last decades these rates were often greatly exceeded by ground compaction rates observed by multi-temporal SAR Interferometry (Gambolati et al. 1998; Antonioli et al. 2017; Polcari et al. 2018; Solari et al. 2018). 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 (Carbognin et al. 2009). Geodetic surveys carried out from 1953 to 2003 along the Ravenna coast provide evidence of a cumulative land subsidence exceeding 1 m at some sites due to gas extraction activities. Average subsidence rates observed for 2006-2011 along the Emilia-Romagna coast are around 5 mm/yr, exceeding 10 mm/yr in the back shore of the Cesenatico and Rimini areas and topping 20-50 mm/yr in Ravenna (Carbognin et al. 2009; Perini et al. 2017). Based on these current rates, we assume an average fixed annual VLM of 5 mm in both Cesenatico and Rimini up to the end of the century. This remarkable difference between natural VLM rates and observations would produce a dramatic effect on the estimated SLR scenarios: at present rates, Rimini would see an increase of MSL by 0.15 m in 2050 and more than 0.4 m in 2100 independently from eustatic SLR. Since these rates are connected with human activity, it is not possible to foresee exactly how they will change in the long term.

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3.3 Sea Level Rise

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 (Thomson et al. 2011), projecting an increase in MSL of 0.53 m at 2100. It must be noted that these projections, although downscaled, 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).

3.4 Tides and meteorological forcing

Storm surge and strong waves represents the largest contribution to TWL during an ESL event. An estimation of these components is obtained for the pilot sites from the analysis of tide gauge and buoy records, and from the description of historical extreme events presented in local studies (Perini et al. 2011, 2012, 2017; Masina et al. 2015; Armaroli and Duo 2018). This area is microtidal: the mean neap tidal range is 30–40 cm, and the mean spring tidal range is 80–90 cm. Most storms have a duration of less than 24 h and a maximum significant wave height of about 2.5 m. During extreme cyclonic events, the sequence of SE wind (*Sirocco*) piling the water North and E-NE wind (*Bora*) pushing waves towards the coast can generate severe inundation events, with significant wave height ranging 3.3 – 4.7 m and exceptionally exceeding 5.5 m (Armaroli et al. 2012). Fifty significant events have been recorded from 1946 to 2010 on the ER coast, with half of them causing severe impacts along the whole coast and 10 of them being associated with important flooding events (Perini et al. 2017). The most severe events are found when strong winds blow during exceptional tide peaks, most often happening in late autumn and winter. The event of November 1966 represents the highest ESL on records, causing significant impacts along the regional coast: the recorded water level was 1.20 m above MSL, and wave heights offshore were estimated around 6–7 m (Perini et al. 2011; Garnier et al. 2018). The whole coastline suffered from erosion and inundation, especially in the province of Rimini. Atmospheric forcing shown significant variability for the period 1960 onwards (Tsimplis et al. 2012), but there is no strong evidence supporting a significant change in trend for the next future (Lionello 2012). Thus, we assume the frequency and intensity of meteorological events to remain the same up to 2100.

3.5 Terrain morphology and coastal defence structures

Reliable bathymetries and topography are required in order to run the hydrodynamic modelling at the local scale. Bathymetric data for the Mediterranean area were obtained from the European Marine Observation and Data Network (EMODnet) at 100 m resolution. The description of terrain morphology comes from the official high-resolution LIDAR DTM (MATTM, 2019). First, we combined the coastal dataset (2 m resolution and vertical accuracy of ± 0.2 m), and the inland dataset (1 m resolution and vertical accuracy ± 0.1 m) into one seamless layer. Then, the DTM is supplemented with geometries of existing coastal protection elements such as jetties, groins and breakwaters obtained from the digital Regional Technical Map. In Rimini, the Parco del Mare is an urban renovation project which aims to improve the seafront promenade: the existing road and parking lots are converted into an urban green infrastructure consisting of a concrete barrier covered by vegetated sandy dunes with walking path. This project also act as a coastal defence system during extreme sea

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level events. The barrier rises 2.8 meters along the southern section of the town, south of the marina; no barrier is planned on the northern coastal perimeter. The Parco del Mare project, currently under construction, has been taken in account in the evaluation of the "defended" scenarios by merging the barrier into the existing DTM (figure **3**).

Figure 3. prototype design of Parco del Mare project in Rimini. Adapted from JDS Architects.

In Cesenatico, the existing defence structure include a moving barriers system (*Porte Vinciane*) located on the port channel, coupled with a dewatering pump which discharge the meteoric waters in the sea. The barriers close automatically if the TWL surpasses 1 meter over the mean, preventing floods in the historical centre up to ESL of 2.2 meters. Additional defence structures include the winter dunes, which consist of a 2.2 meter-tall intermittent, non-reinforced sand barrier. In the defended scenario, we envisage a coastal defence structure similar to Parco del Mare in Rimini, spanning both north and south of the port channel with a total length of 7.8 km. A proper setup of inundation model required to first perform some manual editing of the DTM using additional reference data (i.e. on-site observations or aerial photography) in order to produce an elevation model that realistically represent the land morphology and associated water dynamics (e.g. removal of non-existent sink holes). Bridges and tunnels are the most critical elements corrected in order to avoid misrepresentations of the water flow routing.

3.6 Inundation modelling

At the local scale, hydrodynamic models represent an efficient compromise between hydrostatic and hydraulic models, being able to perform realistic simulations of inundation phenomena and to obtain detailed information about the hazard features, while requiring a relatively fast setup and reasonable computational effort. In this study we use ANUGA, a 2D hydrodynamic model originally developed to simulate tsunami events, which is also suitable for the simulation of hydrologic phenomena such as riverine peak flows and storm surges (Roberts 2020). The fluid dynamics in ANUGA is based on a finite-volume method for solving the shallow water wave equations, thus being based on continuity and simplified momentum equation. The model computes the total water level, the water depth, and the horizontal momentum on an irregular triangular grid based on the provided forcing conditions. ANUGA includes also an operator module that simulates the removal of sand associated with over-topping of a sand dune by sea waves, which is applied to explore scenarios where a sand dune barrier provides protection for the land behind. The operator simulates the erosion, collapse, fluidisation and removal of sand from the dune system (Kain et al. 2020); the dune erosion mechanism relies on a relationship based on Froehlich (2002). This option is enabled only in the undefended scenario for Cesenatico, where non-reinforced sand dunes are prone to erosion.

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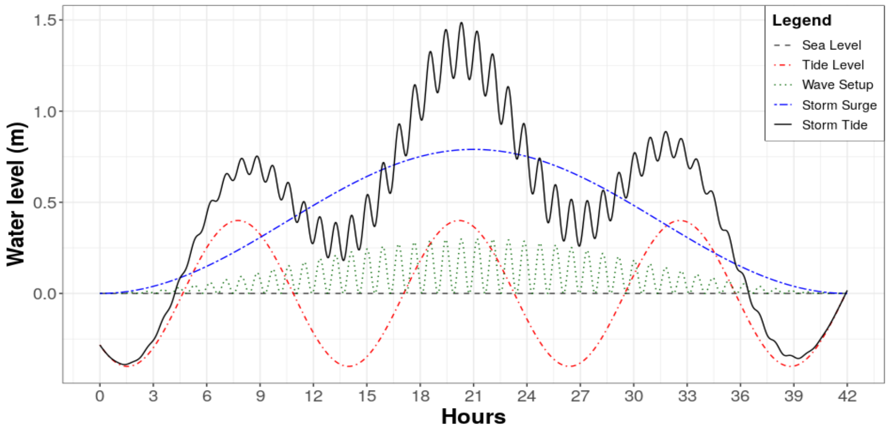

Figure 4. Total Water Level (black) as a sum of tide (red), storm surge (green) and waves (blue) for ESL scenario 1 in 10 years.

TWL on the coastland is modelled at every timestep as the sum of extreme values for storm surge level (*SS*), wave runup (*Wr*), and max tide (*Tmax*), as shown in figure **4**. The maximum tidal excursion is 0.8 m, while wave height can range from 3 to almost 6 m during strong wind events, translated into a wave setup on the shore ranging from 0.22 to 0.65 m. Additional details are wave period (*Wp*, in seconds) and event duration (Time, in hours), required to estimate the maximum extent of inland water propagation. Wave direction is oriented perpendicular to the coast. Storm surge is set to peak in the mid of the event, producing the maximum TWL value for the event. The most exceptional ESL events can last up to 3 days. Table 4 summarizes the ESL components according to the four probability scenarios identified from local historical records (Perini et al. 2017). The probability of occurrence is expressed in terms of return period (*RP*), which is the estimated average time interval between events of similar intensity. Wave run up is calculated from significant wave height. The output of the simulation consists of maps representing flood extent, water depth and momentum at every time step (1 second), projected on the high-resolution DTM grid.

Table 1. components of TWL during an ESL event under historical conditions and projected conditions (2050 and 2100), accounting for both eustatic SLR (RCP4.5) and average VLM rate.

	Extreme event features				**Historical**	**2050**			**2100**		
RP (years)	*SS* (m)	*Tmax* (m)	*Wr* (m)	*Time* (h)	*TWL* (m)	*SLR* (m)	*VLM* (m)	*TWL* (m)	*SLR* (m)	*VLM* (m)	*TWL* (m)
1	0.60	0.40	0.22	32	1.2	0.14	0.19	1.55	0.53	0.44	2.2
10	0.79	0.40	0.30	42	1.5	0.14	0.19	1.82	0.53	0.44	2.5
100	1.02	0.40	0.39	55	1.8	0.14	0.19	2.14	0.53	0.44	2.8
250	1.40	0.45	0.65	75	2.5	0.14	0.19	2.83	0.53	0.44	3.5

3.7 Risk modelling and Expected Annual Damage

Direct damage to physical asset is estimated using a customary flood risk assessment approach originally developed for fluvial inundation, which is adapted to coastal flooding assuming that the dynamic of impact from long-setting floods depends on the same factors, namely: 1) hazard magnitude, and 2) size and value of exposed asset. Indirect economic losses due to secondary effects of damage (e.g. business interruption) are excluded from our computation. Hazard magnitude can be defined by a range of variables, but the most important predictors of damage are water depth and the extension of the flood event (Jongman et al. 2012a; Huizinga et al. 2017). Land cover definitions and buildings footprints help to estimate the exposed capital

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including residential buildings, commercial and industrial activities, infrastructures, historical and natural sites. The characterization of exposed asset is built from a variety of sources, starting from land use and buildings footprints obtained from the Regional Environmental Agencies geodatabases and the Open Street Map database (Geofabrik GmbH 2018). Additional indicators about buildings characteristics are obtained from the database of the official Italian Census of 2011 (ISTAT), while mean construction and restoration costs per building types are obtained from cadastral estimates (CRESME 2014). A depth-damage function previously validated on empirical records (Amadio et al. 2019) and then applied in order to translate each hazard scenario into an estimate of economic risk, measured as a share of total exposed value. The curve covers only residential and mixed-residential buildings; other types (e.g. harbour, industrial, commercial, historical monuments and churches) are excluded from risk computation. Abandoned or under-construction buildings are excluded from the analysis. To avoid overcounting of marginally-affected buildings, we set two threshold conditions for damage calculation: flood extent must be greater than or equal to 10 m², and maximum water depth greater than or equal to 10 cm. The damage/probability scenarios are combined together as Expected Annual Damage (EAD). EAD is the damage that would occur in any given year if damages from all flood probabilities were spread out evenly over time; mathematically, EAD is the integration of the flood risk density curve over all probabilities (Olsen et al. 2015), as in equation 1.

$$EAD = \int_0^1 D(p)\, dp \qquad (1)$$

The integration of the curve can be solved either analytically or numerically, depending on the complexity of the damage function *D(p)*. Several different methods for numerical integration exist; we use an approach where EAD is the sum of the product of the fractions of exceedance probabilities by their corresponding damages. We calculate *D(p)*, which is the damage that occurs at the event with probability *p*, by using a depth-damage function previously validated for Italy on empirical records (Amadio et al. 2019) for each hazard scenario. The exceedance probability of each event (*p*) is calculated based on exponential function as shown in equation 2.

$$p = 1 - e^{\left(\frac{-1}{RP}\right)} \qquad (2)$$

Events with a high probability of occurrence and low intensity (below RP 1 year) are not simulated, and assumed to not cause significant damage. This is consistent with the historical observations for the case study area, although this assumption could change with increasing MSL.

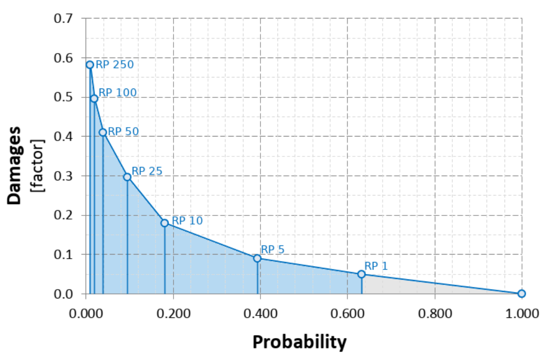

Figure 5. Schematic representation of the numerical integration of the damage function *D(p)* with respect to the exponential probability of the hazard events. Events with a probability of occurrence higher than once in a year are expected to not cause damage (grey area).

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3.8 Cost-Benefit Analysis

A CBA should include a complete assessment of the impacts brought by the implementation of the hazard mitigation option, i.e. direct and indirect, tangible and intangible impacts (Bos and Zwaneveld 2017). The project we are considering, however, has not been primarily designed for DRR purpose: instead, it is meant as an urban renovation project which aims to improve the fruition of the seafront and the urban landscape. This implies some large indirect effects on the whole area, most of which are not strictly related to risk management and, overall, very difficult to estimate ex-ante. Our evaluation focuses only on the benefits achieved in terms of reduction in direct flood losses. The implementation costs include the initial investment required for setting up the adaptation measure, and operational costs through time. The initial investment is estimated to be 6 M Eur per Km. No information is available about operational costs, but given the nature of the project (static defense with very low fragility to floods), we assume they will be rather small compared to the initial investment. We account for ordinary annual maintenance costs as 0.1% of the total cost of the opera. Costs and benefit occurring in the future periods need to be discounted, as people put higher value on the present (Rose et al., 2007). This is done by adjusting future costs and benefits using an annual discount rate (*r*). We chose a variable rate of $r = 3.5$ for the first 50 years and $r = 3$ from 2050 onward (Lowe 2008). The three main decision criteria used in CBA for project evaluation are the Net Present Value (NPV), the Benefit/Cost Ratio (BCR) and the payback period. The NPV is the sum of Expected Annual Benefits (*B*) up to the end of the time horizon, discounted, minus the total costs for the implementation of the defense measure, which takes into account initial investment plus discounted annual maintenance costs (*C*). In other words, the NPV of a project equals the present value of the net benefits ($NB_i = B_i - C_i$) over a period of time (Boardman et al. 2018), as in equation (3):

$$NPV = \mathrm{PV(B)} - \mathrm{PV(C)} = \sum_{t=0}^{n} \frac{NB_r}{(1+r)^t} \tag{3}$$

Positive NPV means that the project is economically profitable. The BCR is instead the ratio between the benefits and the cots; a BCR larger than 1 means that the benefits of the project exceed the costs on the long term and the project is considered profitable. The payback period is the number of years required for the discounted benefits to equal the total costs.

4. Results

4.1 Inundation scenarios

Once the setup is completed, the hydrodynamic model performs relatively fast: each simulation is carried at half speed compared to reality; that means, it takes about 24 hours to simulate a 12 h event. Parallel simulations for the same area can run on a multicore processor, improving the efficiency of the process. The output of the hydrodynamic model consists of a set of inundation simulations that include several hazard intensity variables in relation to flood extent: water depth, flow velocity, and duration of submersion. ESL scenarios are then summarized into static maps, each one representing the maximum value reached by hazard intensity variables at grid cell level (about 1 meter) during the whole simulated event. The flood extents corresponding to each RP scenario are shown for Rimini (figure **5**) and Cesenatico (figure **6**).

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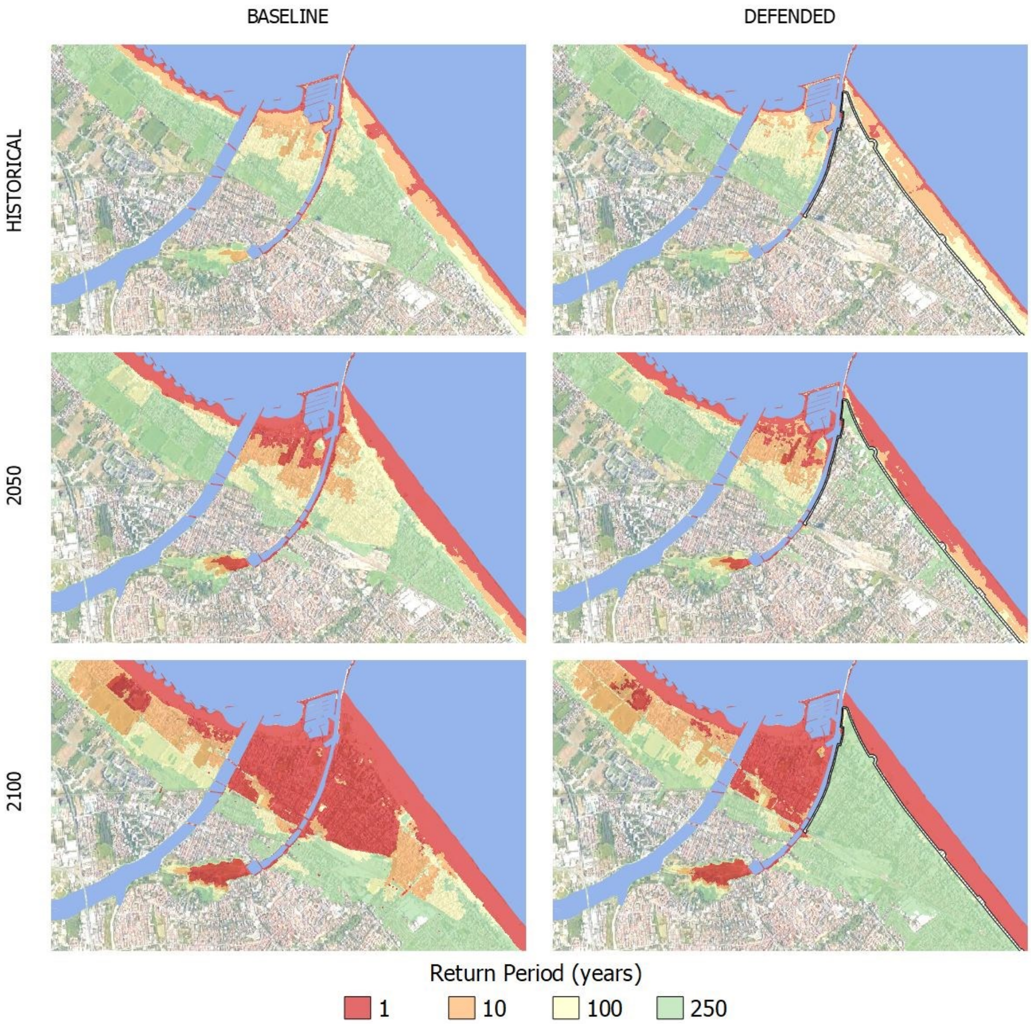

Figure 6. Rimini, extent of land affected by flood according to frequency of occurrence of ESL event up to 2100 for the baseline [left] and the defended scenario [right]. Basemap © Google Maps 2020.

In Rimini, the Parco del Mare barrier produces benefits in terms of avoided damage in the south-eastern part of the town (high-density area) for ESL events with a probability up to 1 in 100 years. The north-western part and the marina are not affected by the coastal renovation project. In all the simulations, the buildings located behind the marina are the firsts to be flooded. In fact, the new and the old port channels located on both sides of the marina represent a hazard hotspot: as shown in the maps, the failure of the eastern channel, which has a relatively low elevation, is likely to cause the water to flood the eastern part of the town, even during inundation events that would not surpass the beach perimeter. In the defended scenarios, where both the coastal and the canal barriers are enabled, the flood extent in the SE urban area becomes almost zero for ESL events with a probability of once in 100 years, even when accounting for SLR up to 2100. Under more exceptional ESL conditions (RP 250 in 2100), the barrier is surmounted, generating a flood extent similar to the baseline scenario.

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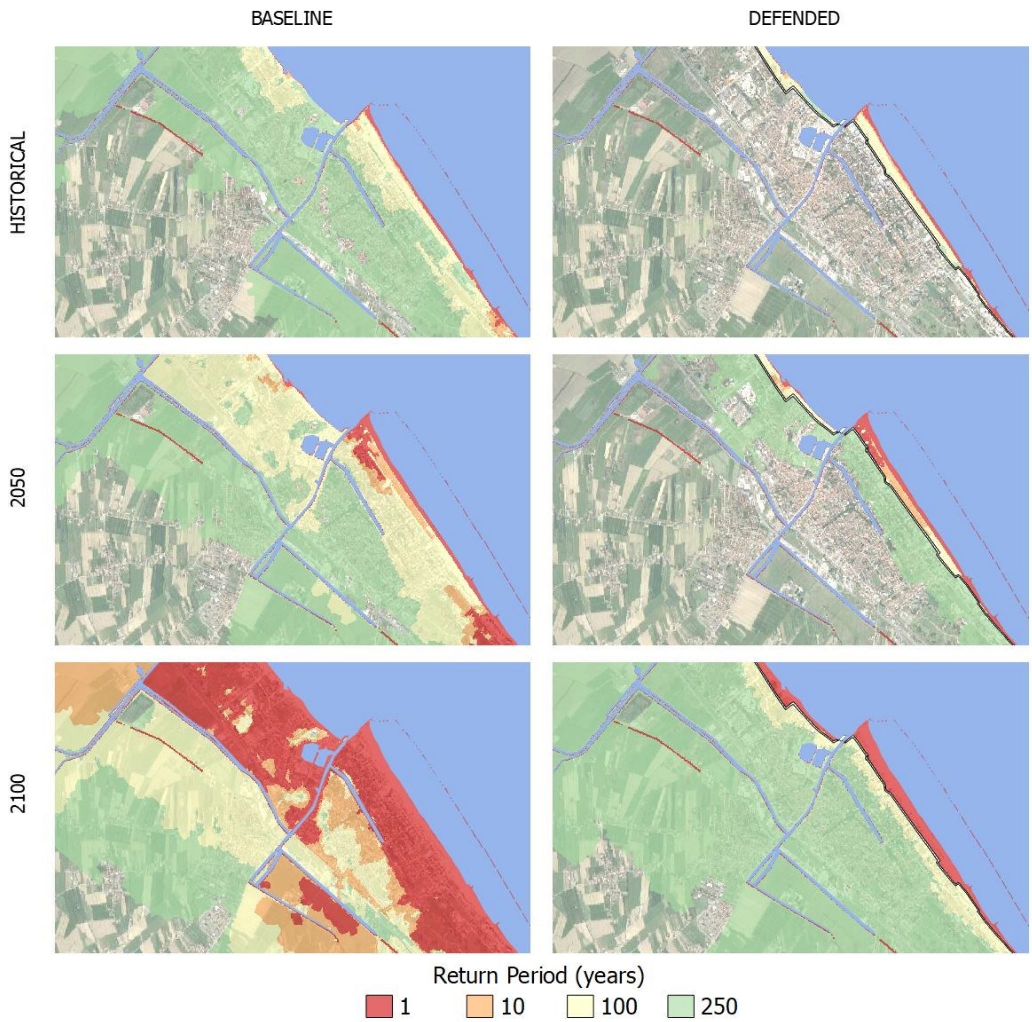

Figure 7. Cesenatico, extent of land affected by flood according to frequency of occurrence of ESL event up to 2100 for the baseline [left] and the defended scenario [right]. Basemap © Google Maps 2020.

In Cesenatico, a barrier designed similarly to Parco del Mare could provide significant reduction of flood extents under most hazard scenarios. Its effectiveness would be greater than in Rimini thanks to the complementary movable barrier system in use, which seals the port channel allowing to wall off the whole coastal perimeter, reducing the chance of water ingression in the urban area. In contrast, the erodible winter dune in the baseline defense scenario can only hold the heavy sea for shorter, less intense ESL events, and becomes ineffective with more exceptional, long-lasting events; at 2050 and 2100, the winter dune gets surmounted and dismantled by sea waves for scenario RP250 years (mid- and low-left maps).

4.2 Expected Annual Damage

The estimate of expected economic impacts calculated as a function of maximum exposed value, and water depth is summarized as Expected Annual Damage in figure **7**, left chart. In Rimini, the EAD grows from around 650 thousand Eur under historical conditions to 2.8 million Eur in 2050 and more than 32.3 million Eur

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in 2100. With less severe events (up to RP 100 years), the risk remains mostly confined around the marina area (outside the protection offered by the reinforced dune) producing an EAD below 10 thousand Eur; with higher water levels (i.e. RP 250 years), the benefits of the dune barrier protecting the southern part of the town become more evident, avoiding about 65% of the EAD. The damage avoided by the barrier in the southern sector (Rimini S) grows almost linearly with the increase of EAD under future projections of sea level rise: under the defended hypothesis, the EAD is reduced on average by 45%. The project produces benefit up to ESL RP250 years in 2100, where a projected TWL of 3.5 meters would cause the surmounting of the barrier, reducing the befits to almost zero (figure **7**, right).

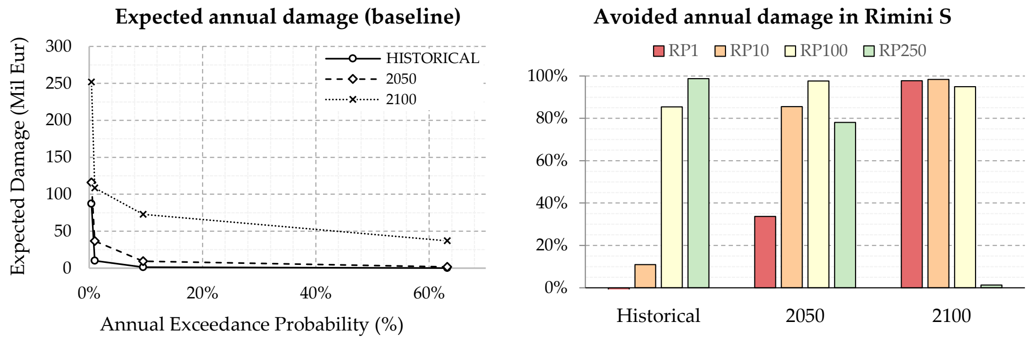

Figure 8. Rimini: Expected Annual Damage (EAD) according to undefended scenario up to 2100 [left]; EAD reduction in the South part of the town thanks to hazard mitigation offered by the coastal barrier [right].

In Cesenatico, the average EAD for the undefended scenario grows from around 270 thousand Eur under historical conditions, to 1.7 million Eur in 2050 and almost 26 million Eur in 2100. In our simulations, the designed barrier (2.8 m barrier along 7.8 km of coast) was able to avoid most of the damage to residential buildings (figure **8**, right). The measure becomes less efficient for the most extreme scenarios in 2050 and 2100, when the increase in TWL cause the surmounting of the barrier. This assessment does not account for the beach resorts and bathing facilities, which are located along the barrier or between the barrier and the sea, and thus are equally exposed in both the baseline and the defended scenario; they would likely represent an additional 7-25% of the baseline damage.

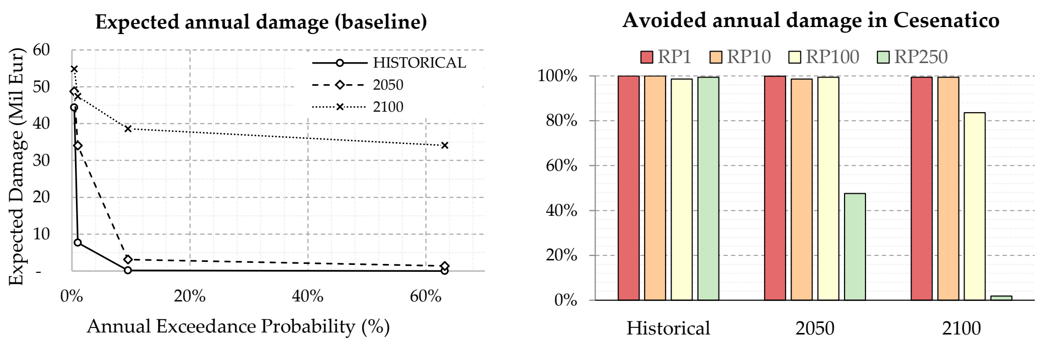

Figure 9. Cesenatico: Expected Annual Damage (EAD) according to undefended scenario up to 2100 [left]; EAD reduction thanks to hazard mitigation offered by the coastal barrier [right].

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4.3 Cost-Benefit Analysis

EAD estimates obtained for both the baseline and the defended scenarios enable to run a CBA to evaluate mitigation measures in terms of NPV, BCR and payback period for the two time-horizons (30 years and 80 years). In figure **9**, the Expected Annual Benefits (EAB) grow at faster rate approaching 2100 in both sites, because of the larger expected damages from more intense, less frequent flood events. The cost of defence implementation is repaid by avoided damage after about 70 years in Cesenatico and after 90 years in Rimini. In Cesenatico benefits grow proportionally to costs, so that the payback time does not change when considering a section of the town or the whole coastal perimeter. At 2100, the BCR is 0.82 for Rimini and 1.66 for Cesenatico, suggesting an overall profitability of the defence structure implementation over the long term. The results in terms of CBR do not differ much when comparing the CBA over a selection of exposed records corresponding to the town higher-density area (i.e. Cesenatico historical center). Table 2 summarizes the metrics of the assessment for different area extent selections. As specified earlier, this assessment does not measure the benefits brought in terms of urban renovation, which are the primary focus of Parco del Mare project, but only the direct benefits in terms of flood damage reduction.

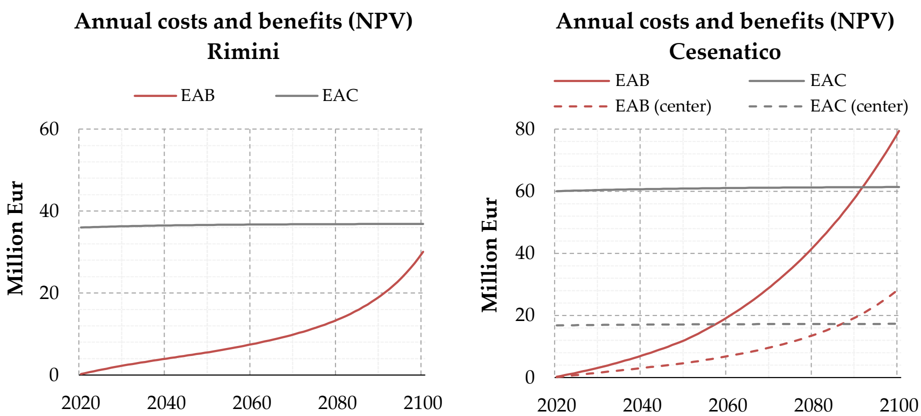

Figure 10. Cumulated flood defence costs and expected benefits at Net Present Value for Rimini (left) and Cesenatico (right).

Table 2. Summary of CBA for planned or designed seaside defence project in Rimini (all town and south section only) and Cesenatico (all town and center only) over a time horizon of 30 and 80 years (2020 to 2050 and 2020 to 2100).

	Rimini				Cesenatico			
	All town		*South only*		*All town*		*Center only*	
Metrics	2050	2100	2050	2100	2050	2100	2050	2100
Baseline EAD [M EUR]	2.8	32	0.5	14.6	1.7	25.9	0.5	12.4
Defended EAD [M EUR]	2.4	17	0.1	0.9	0.1	0.4	0.1	0.4
Expected Annual Benefits [M EUR]	0.4	15	0.4	13.7	1.6	25.5	0.4	11.9
Sum of EAB (discounted) [M EUR]	5.6	30	4.1	27.8	12.0	79.4	4.7	28.6
Sum of EAC (discounted) [M EUR]	36.6	36.9	36.6	36.9	47.4	47.9	17.1	17.3
Net Present Value [M EUR]	-31.0	-6.8	-32.6	-9.1	-35.3	31.5	-12.4	11.3
Benefit-Cost ratio [-]	0.15	0.82	0.11	0.75	0.25	1.66	0.27	1.66

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5. Conclusion

In this study we addressed inundation risk scenarios and measures on two coastal sites located along the North Adriatic coastal plain of Italy, which is projected to become increasingly exposed to ESL events. Both locations are expected to suffer increasing economic losses from to coastal inundation triggered by extreme sea level events unless effective coastal adaptation measures are put in place. To understand the impacts of upcoming ESL events and the potential benefits of designed coastal projects, we run a CBA comparing the baseline and the defended scenario in terms of flood losses. The defended scenario accounts for the effect of a coastal barriers based on the design of the "Parco del Mare", an urban renovation project under construction in Rimini. The same type of structure is envisaged and its effects simulated along the coastal perimeter of the nearby town of Cesenatico. First, we characterised reference ESL events in terms of frequency and intensity based on local historical observations; then, we projected ESL scenarios to 2050 and 2100, accounting for the combined effect of eustatic SLR and subsidence rates on the TWL, as obtained from existing local studies. We produced flood hazard maps estimating maximum flood water extent, water depth and velocity using a high-resolution hydrodynamic model able to replicate the physics the inundation process. The hazard maps were fed to the damage model in order to calculate the expected annual damage for both baseline and defended scenarios. An increase in damage is expected for both urban areas from 2020 to 2100: in Cesenatico the EAD grows by a factor 96, in Rimini by a factor 49.

The results obtained from the CBA on both locations show growing profitability of present project investment over time, associated with the increase of expected annual damage from intense ESL events: the EAD under the baseline hypothesis is expected to increase by 3.5-fold in 2050, up to 10-fold in 2100. The benefits brought by the coastal defence project become much larger in the second half of the century: the EAB grows 6.1-fold in Rimini, 6.5-fold in Cesenatico, from 2050 to 2100. Avoided losses are expected to match the project implementation costs after about 70 years in Cesenatico and 90 years in Rimini. Benefits are found to increase proportionally to costs; the payback period in Cesenatico is the same considering either an investment on the protection of the whole town or only part of it. Further assessments of these renovation projects should look to measure the indirect and spill-over effects over the local economy brought by the project, and possibly account also for the intangible benefits.

Authors contribution

MA, AHE and SB conceptualized the study and designed the experiments. AHE carried out the coastal hazard modelling. SR advised the model setup and calculation. SB and PM provided required data and expertise about the case study areas. MA performed the economic risk modelling and wrote the manuscript. SM supported the CBA calculations. JM and SB managed the funding acquisition and project supervision. All co-authors have reviewed the manuscript.

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Appendix A

A sensitivity analysis is carried out on the discount rate. Figure A1 below shows how the NPV changes with discount rate *r* ranging from 1.5% to 5.5% (2020 to 2050) and 1% to 5% (2050-2100).

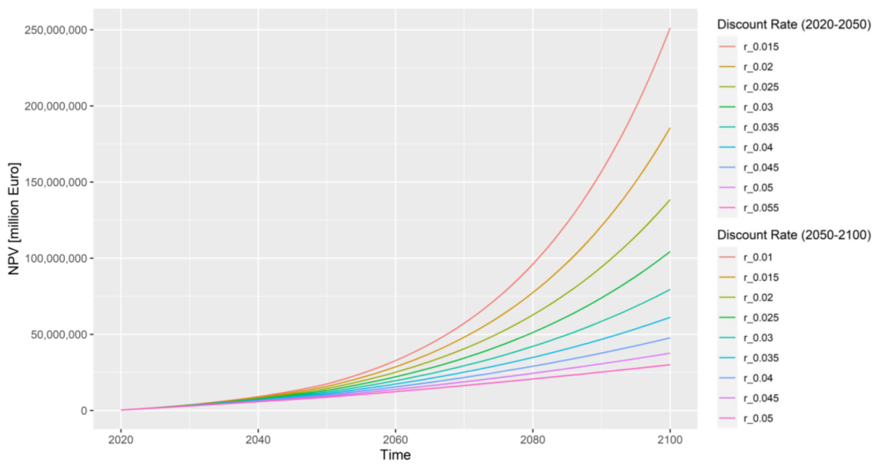

Figure A1. Sensitivity analysis of NPV using a variable discount rate.