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ORIGINAL ARTICLE

The effectiveness of setback zones for adapting to sea-level rise in Croatia

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Abstract

The Mediterranean coastal zone is particularly vulnerable to climate-induced sea-level rise due to rapid coastal development, leading to increased flood exposure in coastal areas. In Croatia, the share of developed coastline is still lower than in other Mediterranean countries, but development has accelerated since the 1960s. Available assessments of future coastal flood risk take into account adaptation by hard structural protection measures but do not consider other options, such as retreat from exposed areas or restricting future development. In this study, we provide the first assessment of the effects of setback zones on future coastal flood impacts on national scale. We extend the flood impact and adaptation module of the DIVA modelling framework with models of restricted future development and slow retreat (managed realignment) in the form of setback zones. We apply this model to a downscaled database of coastal segments of the coastline of Croatia. We find that setback zones are an effective and efficient measure for coastal adaptation. Construction restriction and managed realignment reduce the future cost of coastal flooding significantly, especially in combination with protection. If protection and construction restriction by setback zones are combined, the future cost of coastal flooding can be reduced by up to 39%. Combining protection and managed realignment by setback zones can reduce the future cost of coastal flooding by up to 93%.

Keywords Coastal setback · Construction restriction · Managed realignment · Coastal protection · Coastal retreat

Introduction

For the Mediterranean coast, adaptation to sea-level rise is challenging: growing exposure meets a micro-tidal environment with relatively low surges and only little existing coastal protection. Because of the length of the Mediterranean coast, protection with hard structures or soft measures (e.g. nature-based protection solutions) is not an option for the entire coastline (Baric et al. 2008). Other measures (accommodation or retreat) have to be used for coastal adaptation to rising sea level. The establishment of setback zones is a tool that is increasingly used as part of coastal policies in many countries (Cambers 1998; Marra et al. 1997; Ramsay et al. 2012; Sanò et al. 2011; Shows 1978). Indeed, in 2008, 15 Mediterranean countries signed the Mediterranean Integrated Coastal Zone Management (ICZM) protocol (European Commission 2009; UNEP/MAP/PAP 2008), which requires those countries to establish a 100-m setback zone in unprotected areas, implying no further development (e.g. housing or other infrastructure) within this zone (Rochette et al. 2010). To date, ten countries and the EU have ratified the protocol, which entered into force in 2011.

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While the legal and institutional implications of setback zones have been discussed (Rochette et al. 2010; Sanò et al. 2011), so far no study has quantified the effects of setback zones on the reduction of future sea-level rise impacts. This study addresses this gap by extending a high-resolution integrated flood risk and protection model with a model of slow retreat and restricted future development in the form of setback zones. Although coastal management policies are framed in international settings (i.e. ICZM), they are implemented on a national level. Thus, we apply our model at a national scale for Croatia. With a coastal length of 6278 km (Duplančić Leder et al. 2004), Croatia is among the four Mediterranean countries with the longest coastline (see supplementary material S1). Increasing flood risk is of particular concern in Croatia, due to rapid coastal development along the shore, a growing coastal tourism sector and a lack of existing coastal flood protection. At the same time, coastal development has not yet advanced as far as in many other Mediterranean countries. Croatia ratified the Mediterranean ICZM (Integrated Coastal Zone Management) Protocol (European Commission 2009) and therefore needs to exert some degree of control over future coastal development taking into account sea-level rise that is predicted for the twenty-first century.

The first study of the vulnerability of the Croatian coast to sea-level rise considered two static scenarios of 20 cm and 86 cm (relative to 1985–2005 average sea level), did not account for socio-economic development and was based on expert judgement of the impacts (Baric et al. 2008). The study concluded that the Croatia's coastal areas as they were developed back then in general had a low vulnerability to changes in sea level. The study found that while a sea-level rise of 20 cm would not have significant consequences on the coastal zone in terms of inundation and surge flooding, a sea-level rise of 86 cm would have a much more pronounced effect, primarily in terms of inundation and surge flooding. The first nationwide quantitative assessment of sea-level rise impacts in Croatia was carried out in the context of the Croatian Human Development Report. This study estimated that 50-cm SLR would inundate over 100 km^2 of land, and 88 cm SLR would inundate over 112 km^2, leading to twenty-first century losses in land value of EUR 2.8–6.5 billion and EUR 3.2–7.2 billion (undiscounted 2008 values), respectively (UNDP 2008). These losses were estimated based on minimum and maximum land prices for different land use types (agriculture, forest, roads, railways, urban, etc.). Croatia's Fifth National Communication to the United Nation Framework Convention on the Climate Change subsequently built on these results and emphasized that sea-level rise impacts could potentially be one of the most serious and expensive climate change consequences for Croatia. This report found the most severe SLR impacts to be on commercial and fishing ports, coastal freshwater sources in the karstic zone and coastal touristic and recreational activities (Croatian Ministry of Environmental Protection, Physical Planning and Construction 2010). However, the report did not consider the future development of coastal areas and did not account for possible intense building activities close to the shoreline and thus neither assessed the potential future damage to coastal infrastructure nor evaluates the effects of potential adaptation measures. Finally, a more recent study, Hinkel et al. (2015), using sea-level rise scenarios from 0.28 to 1.08 m in 2100 and different socio-economic scenarios found average annual damages of coastal flooding to amount to US$5.9 to 8.9 billion when no adaptation measures are taken. This study did, however, not take into account the potential implementation of setback zones.

Our study addresses these gaps using the DIVA modelling framework (see "Methods") to conduct a comprehensive analysis of the coastal impacts of sea-level rise for Croatia including the effects of coastal protection and setback zones. We assume protection to be built on the basis of a benefit-cost analysis (Lincke and Hinkel 2018) that takes into account future sea-flood cost (with and without protection) as well as construction and maintenance costs for protection measures. Setback zones are modelled in two ways. In the first model, a construction ban is applied to areas that are not yet developed. This corresponds to how setback zones are currently implemented in Croatia (Rochette et al. 2010). In a second version, setback zones are assumed to be used as a method for managed realignment, where setback zones do not only restrict future construction but also apply to existing buildings and infrastructure. This second version corresponds to managed realignment programs that have been established in many countries (Hino et al. 2017) such as the UK Coastal Change Pathfinder (Defra 2012) and the US Hazard Mitigation Grant Program (Rose et al. 2007).

Methods

Exposure data

Methods for assessing flood exposure are taken from Hinkel et al. (2014). Flood impacts are assessed using the DIVA modelling framework. DIVA (Dynamic Interactive Vulnerability Assessment) is an integrated, global modelling framework for assessing the biophysical and socio-economic consequences of sea-level rise and associated extreme water levels. It combines a database of coastal segments with algorithms assessing different coastal impacts (see supplementary material S2) under a range of physical and socio-economic scenarios, while considering various adaptation strategies (Hinkel and Klein 2009). The default global coastal database, which is part of the DIVA framework, divides the world's coastline (excluding Antarctica) into 12,148 coastal segments (Vafeidis et al. 2008), representing the Croatian coast with 12 segments with a total length of 1850 km. As this level of detail is too coarse for modelling impacts and adaptation at national scale, more detailed data on coastal parameters were provided by the Croatian national authorities (e.g. Ministry of Environmental and Nature Protection). Further, we have used the methods of Wolff et al. (2018) to develop a downscaled segmentation for the Croatian coast. This process resulted in 1560 variable-length (ranging from 0.1 to 116.5 km) coastal segments accounting for a total coastal length of 5800 km (see supplementary material S3).

Each coastline segment represents a one-dimensional bathtub model of the coastal plain. Area exposure is computed from the Shuttle Radar Terrain Mission (SRTM) Digital Elevation Model (DEM) (Rabus et al. 2003) and interpolated piecewise linearly between the given (one metre horizontal resolution) elevation points in order to obtain a continuous distribution of area over elevation. Only those grid cells that are hydrologically connected (using the 8-cell neighbourhood connectivity) to the coast are considered. For a regional study, the common coastal impact analysis approach of projecting assets from global gridded population datasets, such as the GRUMP population data (CIESIN et al. 2011), is not sufficient due to their coarse resolution (see supplementary material S5). Thus, for each segment, asset exposure is obtained by overlaying a nationwide spatial layer of asset values with the exposed area. The layer of asset values was based on county and city spatial plans, census data for population, houses/apartments and flats and the tax data on real estate trading (Pasqual and Markandya 2015).

We assume that currently, there are no dikes in Croatia, which matches well with observations. To account for adaptation to seasonal sea-level variability in unprotected areas, we further assume that no people are living below the height of the 1-in-1-year flood event. Assets below this elevation found in the exposure data are redistributed uniformly to the area between the 1-in-1-year water level and the 1-in-100-year water level.

Spatial information about existing and planned development zones, included in the datasets on assets, is overlayed with the exposed area in order to determine the shares of (i) developed area, (ii) undeveloped area that is approved for future development (called developable area thereafter) and (iii) undeveloped area where future development is not allowed (an example for the vicinity of Rovinj is shown in Fig. 1). Assets and population are only distributed in developed areas. This means that the one-dimensional model of the coastal plain is split into three one-dimensional models for “developed area”, “undeveloped area” and “undeveloped area that is approved for future development” according to the derived shares of the three different zoning types. If the share of a zoning type is zero, the one-dimensional model of this zone has length zero and thus no associated area. Out of the 1560 Croatian coastline segments, 916 contain developed area, 741 contain developable area, 658 contain both zones and 561 contain neither developed nor developable area. See “Results” for an analysis of coastal length and coastal plain for the three different types of areas.

Sea-level rise impacts

Flood impacts are computed as the mathematical expectation of the annual damage to assets taking into account probabilities of extreme water levels (Hinkel et al. 2014). Extreme water level probability density functions are derived from extreme water levels given for different return periods in the GTSR database (Muis et al. 2016). Following Messner et al. (2007), we assess flood damage to assets based on a logistic depth-damage function with a 1-m flood resulting in a 50% loss in asset value. Future extreme water levels are obtained by uniformly displacing the extreme water level distributions upwards with relative sea-level change following twentieth century global observations (Menendez and Woodworth 2010). Beyond this, no change in storm characteristics is assumed. The cost of land loss due to permanent submergence is not assessed following the widely made assumption that submergence by gradual sea-level rise is a slow process, and by the time gradual SLR permanently inundates land, this land has negligible value. Land that has significant value will be protected, or its assets will migrate before inundation (Tol et al. 2016).

Coastal protection

Protection is modelled by means of hard structures (dikes, seawalls, etc.) for each individual segment. It is assumed that protection structures protect an entire coastline segment from flood damages if the protection level is higher than the water level. If the water level is higher than the protection level, we assume the complete failure of the protection structure, and hence the area behind the protection structure is completely flooded. That is, in this case, the water level behind the dikes is the same as in front of the dikes (bathtub model).

As there are no dikes in Croatia today, dike building in our model starts in the 2015–2020 time frame when dikes are constructed according to the cost-benefit optimal protection level, assuming perfect foresight within the SLR and socio-economic scenario used (Lincke and Hinkel 2018). Afterwards, protection levels are kept constant during twenty-first century by raising dikes with sea-level rise in every 5-year step of the model. This follows the Dutch practice of including incremental dike raising in the multi-year dike maintenance cycles (Kind 2014).

To reflect that even if a coastal protection project is efficient in terms of cost-benefit, it might not be implemented due to the availability of alternative projects with higher benefit-cost ratios or financial constraints (Hinkel et al. 2018), we follow current UK practice and only build dikes if the benefit-cost ratio is higher than five (Defra 2011). Similar numbers for

Fig. 1 Coastal development zones around Rovinj in the north of Croatia. Red shaded areas are labelled as developed; green shaded areas are labelled as undeveloped but approved for future development. Unshaded areas are undeveloped and not approved for future development or outside of the 16.5-m elevation zone. Some of the areas approved for future development extend to the shoreline

Croatia or other Mediterranean countries are not available. As this threshold is expected to influence the results significantly, we explore the sensitivity of results by also using threshold values of 2.5 and 7.5.

The cost of protection comprises dike construction and maintenance cost. For dike construction, a unit cost of US$5.8 million per km length and metre height is assumed, based on Vafeidis et al. (2008). These unit costs are taken from Hoozemans et al. (1993) and are based on various Dutch sources and country-specific multipliers from expert judgement. Labour, material, planning and preparation costs are generally included in these sources. Annual dike maintenance cost of 1% of the dike construction cost is assumed (Jonkman et al. 2013).

Setback zones

We model two variants of setback zones. The first variant corresponds to the current legislation in Croatia following Article 8-2 of the Mediterranean ICZM Protocol (European Commission 2009), which requires Mediterranean countries to "establish in coastal zones, as from the highest winter waterline, a zone where construction is not allowed. Taking into account, inter alia, the areas directly and negatively affected by climate change and natural risks, this zone may not be less than 100 meters in width". The article also allows for exceptions from this rule, for instance, "in areas having particular geographical or other local constraints, especially related to population density or social needs, where individual housing, urbanisation or development are provided for by national legal instruments." Given the data and model constraints described above, the following assumptions were incorporated in the DIVA modelling framework in order to implement the statements of the Article:

- Setback zones are only applied to the undeveloped area that is approved for future development. The developed area is generally not declared as a setback zone.

- Setback zone decisions depend on existing or planned protection measures. If an area is protected by dikes (or seawalls) or it is planned to protect the area because protection is economically efficient, it is assumed to be an area of high population density or of general public interest, and therefore no setback zone is established. Only if a segment is not protected and will not be protected in the future, setback zones are applied.
- The shoreline associated with the water level of the highest winter waterline is computed from the maximum high tide–water level from as defined by Pickering (2014). From this shoreline, a 100-m horizontal setback zone is added (Fig. 2).
- The position associated with the setback zone is then computed and transformed into an associated elevation.
- No new construction is allowed within this setback zone. As developable areas are assumed to not contain any construction in the first time step of the model (2015), the initial setback zones in developable areas remain without any assets.
- For each 5-year time step, the setback zone is recalculated taking into account rising sea levels.

The second variant of setback zone is more ambitious than the first variant in that it extends the construction restriction to already developed areas that are not protected by dikes or seawalls. This practice is currently not found in Croatia but corresponds to managed realignment programs as found, for example, in the UK (Defra 2012). In DIVA, we model this as follows: existing exposure within the setback zone is assumed to depreciate gradually with a given annual depreciation rate. The default depreciation rate is 3%, taken as the median value of the depreciation rates derived from rules of the Croatian Financial Ministry and the Croatian Ministry of Construction and Physical Planning. While the former uses, for tax calculations, a depreciation rate of 5% based on assumed lifetime of buildings of 20–25 years (Croatian Ministry of Finance 2004, 2005), the latter prescribes depreciation rates of 1 to 3% for buildings based on economic lifetime of 40–120 years, depending on the building type: hotels 40–80 year, mixed use 50–70, residential 50–70, family houses 60–80, massive family houses 70–100 and luxury family houses 100–120 (Croatian Ministry of Environmental Protection, Physical Planning and Construction 2014).

There is hardly any literature available on costs of establishing setback zones. Shows (1978) estimates the cost of establishing setback initially as US$5600 per km of coastal length, with mandatory 5-year reviews at an expected cost of $11,200 per km. Annual administrative costs could hardly be estimated, but these are assumed to be lower than US$2500 per km (all cost updated to US$ 2015). For construction restriction, the administrative cost is the only cost considered, assuming that the state does not compensate landowners when establishing the building restriction setback zones. Sea-level rise is a slow process; hence, it is justified to assume that land prices generally depreciate once potential buyers and landowners become aware of the threat (or see the actual impact) of flooding or erosion (Yohe et al. 2011).

In the case of managed realignment, it is assumed that in addition to the administrative costs reported above, the government compensates homeowners for their lost assets. As our model operates at national scales, we cannot model the timing of the buyout for individual buildings. Hence, we assume that in each time step, the government compensates the value of assets that are depreciated in that time step. This gives the same results as modelling individual buyouts if one assumes that individual buyouts would be distributed evenly over space and time (Fig. 3).

Adaptation strategies

The two protection modes and the three setback zone modes are combined into the following six adaptation strategies.

1. No adaptation: No dikes are built, and no setback zones are established. Socio-economic development in the coastal zone continues to follow the asset growth scenarios based on the shared socio-economic pathways (SSPs).
2. Construction-restriction: No dikes are built, but in developable areas, the 100-m setback zone is established in such a way that no construction is allowed in this zone. No restrictions apply for developed areas – they continue to develop according to the socio-economic scenario. Due

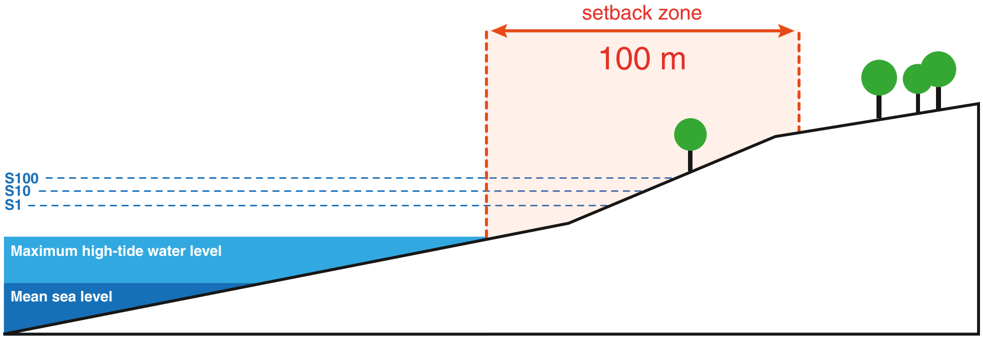

Fig. 2 The setback zone in the coastal plain model of DIVA

Fig. 3 Schematic presentation of the different setback approaches used in the study. White houses exist, while light green houses represent future construction, and red houses exist but are in the phase of depreciation and thus will disappear

to rising sea levels, the expected annual flood damages in these areas rise over time.

3. Managed realignment: No dikes are built, but in both developable and developed areas, the 100-m setback zone is established. No construction is allowed in this zone in developable areas, and assets depreciate in developed areas.
4. Protection only: In the first iteration of the model (representing year 2015), the protection level with the highest benefit-cost ratio is computed applying a discount rate of 3.0% to future costs. If the highest benefit-cost ratio of any protection level is larger than five, it is implemented as a dike (immediately). Dikes are raised with sea-level rise as described above. Setback zones are not established.
5. Protection combined with construction-restriction: Dikes are built as in the dikes-only strategy above. In addition, setback zones that do not allow for construction in developable areas are established in segments without protection by dikes.
6. Protection combined with managed realignment: Dikes are built as in the dikes-only strategy above. In addition, setback zones that do not allow for construction in developable areas and that depreciate assets and population in developed areas are established in segments where no dike exists.

Scenarios

Scenarios of sea-level rise as well as socio-economic development are considered in this study. Sea-level rise scenarios are taken from Kopp et al. (2014), who provides probabilistic projections for seven Croatian tide-gauge sites (see supplementary material Figure S3). While Kopp et al. (2014) provide probabilistic projections in the form of 33 percentiles per RCP and location, we only use two scenarios here to keep complexity low. The 50th percentile of RCP4.5 will be used as a medium scenario, and the 95th percentile of RCP8.5 will be used as high scenario. While RCP4.5 roughly represents a 2-degree world, RCP8.5 represents a world where mean temperature is expected to rise significantly more than two degrees, with the 95th sea-level rise quantile of RCP8.5 often being used as a high-end scenario. The range of projected sea-level rise values over the seven Croatian tide-gauge sites for 2050 is 0.17–0.19 m for the 50th percentile of RCP4.5 and 0.36–0.49 m for the 95th percentile of RCP8.5. For 2100, the ranges are 0.40–0.47 m for RCP4.5 and 0.96–1.06 m for RCP8.5 (all values are relative to the mean sea level in the base year 2000). The values for each coastline segment are taken from the nearest tide-gauge site.

Croatian national socio-economic projections from the global shared socio-economic pathways (IIASA 2012) are used for population projections, but are not used for asset projections as there is a big discrepancy between population projections and the expected intensification of coastal urbanization. Since the 1960s, the population of Croatia grew by only 3%, while 4 times more was built than what all previous generations had built (Croatian Institute for Spatial Planning 2013). National and international population projections for Croatia all indicate a decrease in population numbers. However, spatial plans in Croatia foresee a massive increase of the urbanized coast. Thus, SSP-based (for SSP1, SSP2 and SSP5) coastal asset projections for Croatia from Pasqual and Markandya (2015) are used to project future assets in the coastal zone (see also supplementary material S4). As these projections end in 2050, they have been extrapolated linearly until 2100. The asset value projections are applied to the coastline segments considering the different development zones. In an “intense coastal compacting phase” from 2020 (now) to 2035, the asset growth is distributed in a way that the asset density in 2035 is equal for developed and developable areas within a segment, with the national sum of assets growing according to the national asset growth rate. Thus, different growth rates for developed and developable areas are computed and applied. Then, the asset growth is distributed proportionally between the different zones. For these few segments (83 out of 1560) that do not have a developed zone but only an undeveloped zone that is approved for future development, asset growth is assumed such as that at the end of the intense coastal compacting phase, the asset density in these developable zones equals the national asset density average over all developed zones.

Table 1 Characteristics of the coastal zone below 16.5 m of the Republic of Croatia

	Total	Developed land	Developable land
Area above the 1-in-1-year water level (km^2)	1163.8	144.7 (12.4%)	64.8 (5.6%)
Coastal length (km)	5821	597.6(10.3%)	258.5 (4.4%)
1-in-100-year floodplain (km^2)	133.2	12.8 (9.6%)	6.6 (5.0%)

Results

Existing construction and setback area

The coastal zone (comprising the regions with elevation lower than 16.5 m) of Croatia accounts for an area of approximately 1160 km^2 (Table 1) distributed over the 5820 km of coastal length. About 12% of the coastal zone and 10% of the coastal length are already developed, and almost 50% of the remaining area is declared as developable area.

In the adaptation strategies with setback zones, the length of the coastline declared as setback zone in 2015 is between 195 and 856 km. The setback area associated with these lengths is between 19.6 and 80.9 km^2, depending on SLR, protection and setback method (construction restriction or managed realignment). As setback zones are reviewed and adjusted every 5 years, the setback area grows with SLR from 21.7 to 107.1 km^2 until 2100 (Table 2 and Figure S6 in the supplementary material). The length of setback coastline however remains constant as the review and adjustment do not involve declaring additional coastline as setback zone. The setback zone with protection is larger for RCP 4.5 (compared with RCP 8.5) as protection depends on benefit-cost analysis. Thus, more coasts are protected under RCP 8.5 than under RCP 4.5 (see below), and thus the setback area in the unprotected coast is larger under RCP 4.5.

The setback area in 2015 comprises up to 44% of the developed and developable coastal zone of Croatia, because the Croatian coast is rather steep and a 100-m setback zone reaches beyond the 16-m elevation for more than 50% of the coastline. As a consequence, setback zones move the construction line above the 1-in-100,000-year water level in 2015 for more than 98% of the coast.[1]

If setback zones only restrict construction in developable areas, they do not affect any existing assets (as by definition, no assets are located in developable areas in 2015). If managed realignment is incorporated in the development of setback zones, assets worth US$7.5–13.4 billion are located in the setback area in 2015. The amount of assets in the setback area increases over time with the inland extension of setback zones due to SLR and decreases with the depreciation of existing asset values in the setback zone. The effect of the depreciation is bigger leading initially to a slightly falling trend of asset values in the setback zone, which then stabilizes in the second half of twenty-first century.[2]

Cost of sea-level rise

The total costs of sea-level rise and its components (flood cost, protection construction cost, maintenance cost, setback depreciation and administration cost) in Croatia under the different adaptation strategies are shown in Fig. 4 (annual cost and components for RCP8.5 over time[3]). In terms of flood costs, protection and setback reduce the total coastal cost significantly. Without protection, construction restriction reduces total coastal cost in 2100 by approximately 7% (RCP 4.5) and 22% (RCP 8.5).[4] Managed realignment reduces the total cost by up to 85% (RCP 4.5) and up to 86% (RCP 8.5). Protection measures alone reduce the total cost in 2100 by up to 71% for RCP 4.5 and up to 80% for RCP 8.5. If in addition to protection a construction restriction is implemented, total costs in 2100 are reduced by 9% (RCP 4.5) and 36% (RCP 8.5) compared with protection alone. Combining protection with managed realignment reduces the total cost in 2100 by up to 77% for RCP 4.5 and up to 80% for RCP 8.5, compared with protection without setback zones. Compared with the case of no protection and no setback (highest total cost), protection combined with managed realignment reduces the total costs in 2100 by up to 96%.

Expected annual sea flood cost[5] without protection and without setback zones are predicted to rise from US$10–40 in 2015 to US$1.3–1.7 billion under RCP 4.5 and US$4.5–5.8 billion under RCP 8.5 in 2100. Under all protection and setback strategies, flood costs are predicted to rise throughout the twenty-first century. However, protection and setback reduce future flood costs significantly. Without protection, construction restriction can reduce predicted flood costs in 2100 by 10% (RCP 4.5) and 23% (RCP 8.5). Managed realignment reduces predicted sea flood costs in 2100 by up to 94% (RCP 4.5) and 90% (RCP 8.5). Protection measures without setback zones reduce predicted flood costs in 2100 by 71% (RCP 4.5) and 80% (RCP 8.5). If protection is combined with

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[1] Table S4 and Figure S6 in the supplementary material show the relation between setback zone, elevation and extreme water level return period.

[2] Figure S8 shows the projected assets in the setback zone in Croatia over the twenty-first century.

[3] Additional figures can be found in the supplementary material: S10, RCP 4.5 over time; S09, both RCP over time including socio-economic uncertainty; and S11, accumulated total cost over twenty-first century.

[4] For detailed numbers, see Tables S5 and S6 in the supplementary material.

[5] Detailed results can be found in the supplementary material: Figure S12, sea flood cost over time (both RCPs); Figure S13, local distribution of sea flood cost; and Table S7.

Table 2 Setback zone area under the adaptation strategies and SLR scenarios used in this study. The range in the values involving protection represents the range over the socio-economic scenarios (which protection building depends upon)

	Length of setback coastline (km), 2015		Setback area (km^2), 2015		Setback area (km^2), 2100	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Construction restriction, no protection	258.5	258.5	24.0	24.2	28.0	33.1
Construction restriction, protection	215.8–219.7	194.9–195.5	19.6–20.0	17.6–17.6	21.8–22.3	21.7–21.8
Managed realignment, no protection	856.1	856.1	80.2	80.9	92.1	107.1
Managed realignment, protection	690.5–703.4	596.4–607.0	63.3–64.6	54.1–55.2	69.2–70.8	64.3–65.6

a construction restriction, flood costs in 2100 are reduced by 17% (RCP 4.5) and 37–39% (RCP 8.5) compared with protection without setback zones. Managed realignment combined with protection reduces the 2100 flood cost by 93% (RCP 4.5) and 87% (RCP 8.5) compared with protection without setback zones.

Although previous studies have not used asset data that is as empirical and spatially explicit as those used in this study, the results are in the same order of magnitude as the results of earlier studies. Using a hydrodynamic modelling approach, Vousdoukas et al. (2018) estimated annual flood cost without adaptation in 2100 for Croatia to be €1.6 billion under RCP4.5 and SSP1 and €4.6 billion under RCP8.5-SSP5. Taking into account exchange rates, these results match very well with the numbers in this study.

As there is no initial protection in place, adaptation strategies that involve protection need to build a significant amount of dikes in the first time step of the model (Fig. 4). Under the benefit-cost analysis-based protection model used in this study, 272 (RCP 4.5) to 443 km (RCP 8.5) of coast are protected in the first time step. As the extreme water levels are rather low, the average initial dike height for the 272 km of coast protected under RCP 4.5 is 0.73 m, which corresponds to a protection level of 660 (meaning that the local protection in average protects against the 1-in-660-year event). Under RCP 8.5, the average initial dike height is 0.81 m, corresponding to a protection level up to the 1-in-730-year event. As described in "Methods," protection levels are kept constant which means dikes are raised with sea-level rise to 1.13 m (RCP 4.5) and 1.72 m (RCP 8.5) in 2100. The initial costs for building these dikes are US$ million 362 (RCP 4.5) and 655 (RCP 8.5). For the remainder of the twenty-first century, US$ million 5.2–8.2 (RCP 4.5) to US$ million 13.5–23.1 (RCP 8.5) would be required annually for protection upgrading and maintenance.[6]

In the first time step, the costs of the construction restriction strategy only include the administrative cost but not asset depreciation (Fig. 4). As the setback zones are adjusted with growing SLR, annual setback zone depreciation costs are up to US$34 million/year with additional protection and up to US$64 million without additional protection.[7] Conversely, as setback zones under the managed realignment adaptation strategy initially contain significant assets (see above), depreciation starts immediately when setback zones are established. Initial annual depreciation cost ranges from US$203 (RCP 8.5, with additional protection) to US$331 million (RCP 8.5, no additional protection) and declines to US$66 (RCP 4.5, with additional protection) to US$203 million (RCP 8.5, no additional protection). Under the adaptation strategies that include additional protection, the higher initial values for RCP 4.5 as compared with RCP8.5[8] results from the higher share of coastline protected under RCP 8.5.

This is the first study that explores the effect of different setback measures on national scale. Previous studies and guidelines have explored the legal and administrative issues of setback zones (Rochette et al. 2010), the role of setback zone in the general context of coastal management (Sanò et al. 2011) or technical aspects in defining setback zones (Marra et al., 1997; Ramsay et al. 2012). None of these studies estimates the effect of setback zones on future coastal impacts; thus, we are not able to compare our results with earlier studies.

Sensitivity analysis

Discounting of future cost in the protection decision and the depreciation of future value of assets are parameters that affect results considerably. To explore the sensitivity of our results to this source of uncertainty, the analysis was repeated with five discount rates and depreciation rates from 1.0 to 5.0. Using a discount and depreciation rate of 5.0 instead of 3.0 decreases

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[6] Figure S14 in the supplementary material provides the projected annual protection cost over twenty-first century for both RCPs.

[7] Figure S15 in the supplementary material shows the projected coastal asset depreciation over twenty-first century for both RCPs and the four relevant setback and protection scenarios.

[8] The difference can be seen in Figure S8 in the supplementary material which shows the projected value of all assets in the setback zone over time if it is assumed that setback zones are used for managed realignment.

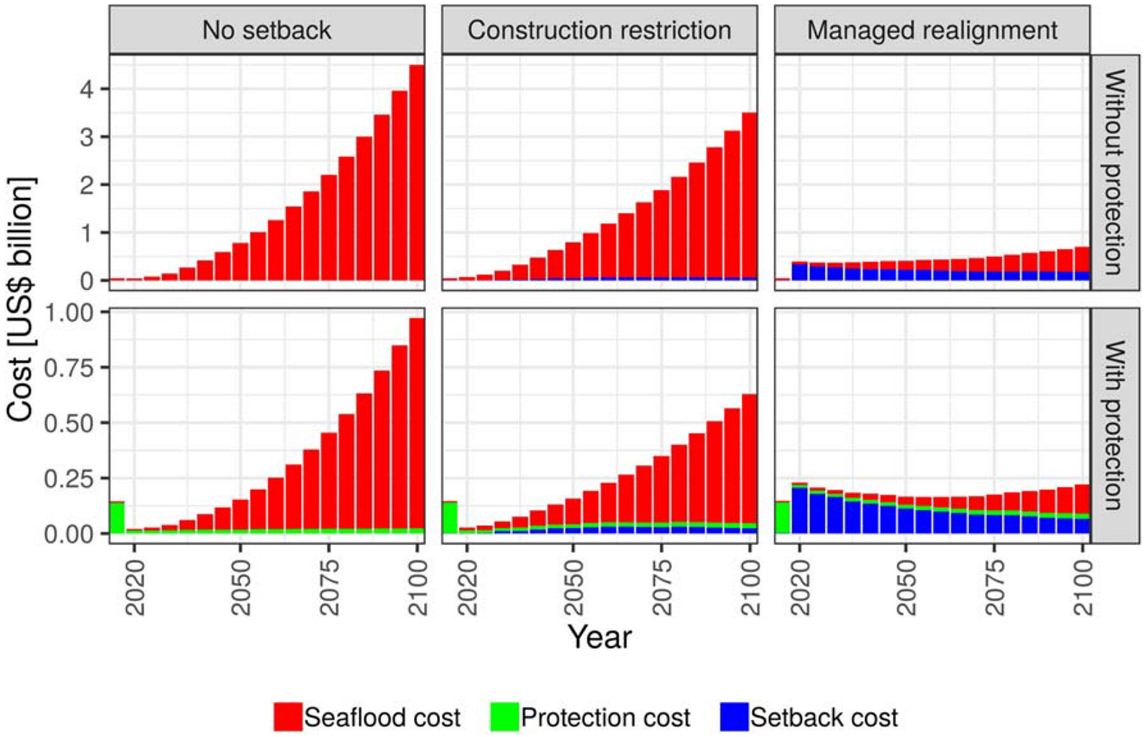

Fig. 4 Total cost of sea-level rise and its components under RCP8.5 sea-level rise, the SSP2 asset growth scenario and the adaptation strategies considered in this study

the length of protected coast by 34% and increases the length of setback coast by 14% under the protection and managed realignment adaptation strategy and RCP 8.5. Under the same assumptions, the total cost in 2100 falls by 3%. Using a discount and depreciation rate of 1.0 instead of 3.0 increases the length of protected coast by 42% and decreases the length of setback coast by 11%, while the total cost in 2100 rise by 8% under the protection and managed realignment adaptation strategy and RCP 8.5. While the patterns in length of protected coast and setback length remain the same under the other adaptation strategies and also under RCP 4.5, there are significant differences for the total cost in 2100. These costs are dominated by flood costs and are thus highest under RCP8.5 combined with the protection and construction restriction adaptation strategy.

We also varied the benefit-cost ratio threshold for protection implementation over the values 2.5, 5.0 and 7.5. Under the protection and managed realignment adaptation strategy and RCP 8.5, the length of protected coast increases by 41%, and the length of setback coast decreases by 10% when using a threshold of 2.5 instead of 5.0. A threshold of 7.5 decreases the length of protected coast by 22% and increases the length of setback coast by 8% under the protection and managed realignment adaptation strategy and RCP 8.5. Total cost in 2100 is 10% lower for the threshold 2.5 and 7% higher for threshold 7.5. As was the case for the depreciation and discount rates, the patterns in length of protected coast and setback length remain the same under the other adaptation strategies and also under RCP 4.5, while there are significant differences for the total cost in 2100.[9]

Discussion and conclusion

In this study, we have performed the first national-scale assessment (for the entire coastline of Croatia) of the effectiveness of setback zones as a coastal adaptation measure. We introduced two versions of setback zones as an adaptation measure into the DIVA modelling framework. The first version defines setback zones as restricting future construction and only limits future asset development. This is the way setback zones are used today in many Mediterranean countries. The second version does not only restrict new construction in the setback zone but also requires existing buildings and infrastructure to be relocated away from the flood zone.

For both versions of setback zones, we analysed for the entire coastline of Croatia the costs and benefits of setback zones in combination with coastal protection based on

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[9] Additional figures and tables can be found in the supplementary material: Table S8 shows the sensitivity of protection and setback length and total cost of sea-level rise to different discount and depreciation rates with fixed benefit-cost ratio threshold for protection. Table S9 shows the results if benefit-cost ratio threshold for protection is varied and discount and depreciation rate is fixed. Figure S16 and S17 show the total cost of sea-level rise and its components under the RCP8.5 sea-level rise and the SSP2 for different discount and depreciation rates respectively different benefit-cost ratio thresholds for protection.

benefit-cost analysis. Our key finding is that monetary sea-level rise impacts (damages due to increased coastal flooding and adaptation cost for upgrading and maintaining coastal protection infrastructure) can be significantly reduced by integrating setback zones into the adaptation strategy. We showed that a combination of construction restriction by setback zones and protection reduces impacts by an order of magnitude compared with no adaptation measures. Although the larger share of the reduction comes from protection measures, a construction ban by setback zones adds a further impact reduction of up to 36%. Setback zones as a measure for managed realignment reduce impacts even more (up to 80%). A combination of managed realignment by setback zones and protection reduces impacts by two orders of magnitude compared with the base line strategy without any adaptation measures.

We must note that there are many simplifications in the representation of the underlying physical and economic processes, and thus the scope of the paper is rather to provide a first-order indication of total costs and the order of magnitude of cost reduction for the different strategies.

Limitations of our study include that it does not take into account benefits of setback zones beyond reducing exposure to coastal flooding. We disregard the benefit of setback zones on biodiversity protection and maintaining ecosystem services. Further, setbacks also help to slow down the natural erosion of coastal systems: for instance, beach loss can be considerably enhanced by hard coastal protection measures. Setback zones can prevent such beach loss. This aspect is not included in this study as it hardly applies to Croatia: there are only very few erodible beaches as most beaches consist in pebbles that erode much less than sandy beaches.

Although we present very exact values, the scope of the paper is rather to provide indication of total costs for the different strategies. We note that there remain large uncertainties in the underlying input data (Hinkel et al. 2014; Wolff et al. 2016) and in the modelling of physical processes (Vousdoukas et al. 2018), which can significantly affect the results. Another limitation of the DIVA modelling framework is that the stylized bathtub representation of flood propagation as often applied in large-scale assessments might overestimate flood extent and damages as compared with detailed local hydrodynamic flood propagation models (Giardino et al. 2018). As the Croatian coast is rather steep and the floodplain rather narrow, this effect should however be small in this case.

A further limitation of this work lies in the lack of data on the costs of setback zones and specifically managed realignment. While construction restriction with setback zones is a rather low-cost measure, managed realignment by setback zones can have costly consequences for both homeowners and governments. Future work should further explore these direct and indirect costs. Furthermore, many more variants of setback zones and managed realignment are found around the world beyond the proactive variants as modelled in this study. For example, setback zones have also been established as reactive responses to major coastal flood events such as the storm Xynthia, which flooded several low urbanized areas on the French Atlantic coast in 2010, causing the death of 41 people. Houses located within the disaster zone were first purchased by the state following the storm and are now gradually being torn down (Mercier and Chadenas 2012).

Finally, regional and country level adaptation research needs to take advantage of other existing approaches, such as adaptation pathways (Haasnoot et al. 2013) which could be combined with our setback modelling to find robust and acceptable long-term solutions to SLR. This would also require intense stakeholder involvement (Mielke et al. 2017), for instance, by exploring how local communities can be engaged in regional responses and including a wide range of adaptation options and strategies. Coastal adaptation also needs to take into account the wider objectives of coastal management and development as well as the interests and conflicts among diverse stakeholders (Bisaro and Hinkel 2016). For example, protecting via dikes will not be attractive for the tourism sector; setback zones will not be favoured by the real-estate sector; and managed realignment would be opposed by home and landowners. Such economic, financial and social barriers to adaptation often delay or prevent projects (Hinkel et al. 2018) and need to be taken into account in order to develop robust adaptation plans.

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