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Assessment of Costs of Sea-Level Rise in the Republic of Croatia Including Costs and Benefits of Adaptation

Integration of Climatic Variability and Change into National Strategies to Implement the ICZM Protocol in the Mediterranean

Technical report

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MINISTRY OF ENVIRONMENT AND NATURE PROTECTION

PAP/RAC

Report:

Assessment of Costs of Sea-Level Rise in the Republic of Croatia Including Costs and Benefits of Adaptation

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Mitraković, B. (2015)

Garbin is a mean wind

Slobodna Dalmacija, February 1, 2015, Komiža, island of Vis

… Around 11 p.m. my mum and I were watching TV when she alerted me that the sea was entering our house under the front door, so we started wiping the sea water that was entering from all directions.

We leaned against the door trying to hold it closed when there was a bang and we were suddenly in the sea which had filled our living room.

At that moment something hit me, a wardrobe or something, and I kept calling my mother asking her if she was alive.

She replied, she was also injured. We somehow managed to run upstairs to the first floor where we changed into dry clothes, I got her warm and that's how we stayed until the morning.

In all that confusion I lost my mobile phone and my glasses, a part of the house is totally destroyed, a doctor came to visit us… – Tanja P. told us, still in shock.

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List of Acronyms

BRANCH	Biodiversity Requires Adaptations in Northwest Europe under a CHanging climate
CGIAR-CSI	Consultative Group on International Agricultural Research – Consortium for Spatial Information
CIAT	International Center for Tropical Agriculture
CIESIN	Center for International Earth Science Information Network
CLIMATECOST	Full Cost of Climate Change (project)
CMIP5	Coupled Model Intercomparison Project Phase 5
CV&C	Climatic Variability and Change
DEM	Digital Elevation Model
DG	Directorate-General
DINAS-COAST	Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise (project)
DIVA	Dynamic Interactive Vulnerability Assessment
DTM	Digital Terrain Model
EACC	Economics of Adaptation to Climate Change
EEA	European Environment Agency
EMFF	European Maritime and Fisheries Fund
ESRI	Environmental Systems Research Institute
EU	European Union
EUR	Euro (currency)
FAO	Food and Agricultural Organisation
GADM	Global ADMinistrative areas
GDP	Gross Domestic Product
GEF	Global Environment Facility
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GrIS	Greenland Ice Sheet
GRUMP	Global Rural-Urban Mapping Project
HadGEM2-ES	Hadley Centre Global Environmental Model, version 2 (Global climate model)
HTM	Hamburg Tourism Model
ICZM	Integrated Coastal Zone Management
inh.	Inhabitants
IMAGE	Integrated Model to Assess the Global Environment
IMPACT2C	Quantifying projected impacts under 2 degree C warming (project)
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	IPCC Fifth Assessment Report
IPFRI	International Food Policy Research Institute
km	kilometre
LECZ	Low Elevation Coastal Zone
LOICZ	Land Ocean Interactions in the Coastal Zone
MAR	Regional climate model (in French: Modèle atmospherique regional)
MSL	Mean Sea Level
N/a	Not available (data)
PAP/RAC	Priority Actions Programme – Regional Activity Centre
PESETA	Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis
RCP	Representative Concentration Pathway
SeaRISE	Sea-level Response to Ice Sheet Evolution
SED	Socio-Economic Development
SLR	Sea Level Rise
SMB	Surface Mass Balance
SRES	Special Report on Emissions Scenarios

SSP	Shared Socio-economic Pathways
SRTM	Shuttle Radar Topography Mission
TIN	Triangulated Irregular Network
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
US$	US Dollar

1 Introduction

The Climate Variability Project has been designed to support the implementation of the ICZM Protocol in the Mediterranean. The objective of the project is to create an enabling environment for the integration of climatic variability and change (CV&C) adaptation strategies into ICZM policies, plans and programs of Mediterranean countries by:

(i) strengthening the understanding of the impacts of CV&C on the coastal zones of the Mediterranean region; and

(ii) establishing the needed information exchange mechanisms, capacity and regional pilot experiences.

As a contribution to the second objective, a top-down, national-level assessment of sea-level rise impacts has been carried out for Croatia and Tunisia, which have been chosen as two pilot sites. This document reports the results for Croatia.

Most work on climate change impacts for Croatia has focused on changes in temperature and precipitation (e.g. Branković et al., 2009, 2012). Early assessments of sea-level rise vulnerability have identified the historical town centres and the alluvial plain of the Neretva River, and Vrana Lake on the island of Cres as seriously vulnerable, but relied on qualitative expert judgement (Barić et al., 2008). The first quantitative assessment of sea-level rise (SLR) impacts, carried out in the context of the Human Development Report Croatia, 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 losses in land value of EUR 2.8–6.5 billion and EUR 3.2–7.2 billion, respectively (UNDP, 2009). These losses were estimated based on minimum and maximum land prices for different land use types (agriculture, forest, roads, railways, urban, etc.). The Fifth National Communication of the Republic of Croatia under the United Nations Framework Convention on Climate Change (UNFCCC) reiterates these results and emphasises that sea-level rise impacts could potentially be one of the most serious and expensive climate change consequences for Croatia (Ministry of Environmental Protection, Physical Planning and Construction, 2010). The cities of Nin, Zadar, the area of Šibenik, Split, Stari Grad and Dubrovnik are seen as particularly vulnerable zones.

This report presents a novel quantitative country-wide assessment of the sea-level rise related climate impacts for Croatia. The top-down methodology builds upon the experience of the DIVA (Dynamic and Interactive Vulnerability Assessment) model and database. DIVA is an integrated, global modelling framework for assessing the biophysical and socio-economic consequences of sea-level rise and associated extreme water levels, under different physical and socio-economic scenarios and considering various adaptation strategies (www.diva-model.net, Hinkel and Klein, 2009). DIVA is a modular model that assesses several impacts of sea-level rise (See Figure 1). For this assessment we focus on the impacts of:

- Increased coastal flood risk in terms of the expected annual damages of extreme sea level events (storm surges), in terms of monetary damages to assets (buildings, infrastructure) and number of people affected.
- Dry land loss due to increased coastal erosion due to sea-level rise and resulting damages (forced migration).

Both of these impacts have not been assessed for Croatia before. The aforementioned UNEP report focused on the impact of the gradual submergence of low-lying land. It is, however, important to note that even before sea-level submerges low-lying land, sea-level rise may have significant impacts by raising extreme water levels and causing coastal floods. This impact is more immediate, affects a greater area than sea-level rise submergence and is expected to be much more costly than the impact of submergence (Wong et al., 2014). This study also goes beyond previous ones in that it also quantifies the costs of adaptation strategies.

The DIVA model was co-developed with, and builds upon, a global coastal database that contains information on biophysical and socio-economic coastal characteristics (Vafeidis et al., 2008). The database relies on a segmentation of the world's coasts (excluding Antarctica) into 12,148 linear segments and associates with each segment about 100 elements of data concerning the physical, ecological and socio-economic characteristics of the coast. This approach has been unique in the sense that it integrates data and methods for studying coastal processes from a range of different disciplines.

DIVA has been widely used for global and continental scale assessments of sea-level rise impacts, vulnerability and adaptation (e.g. Hinkel et al., 2009; Nichols et al., 2010; McLeod et al., 2010; Hinkel et al., 2010, 2011; Vafeidis et al., 2012; Hinkel et al., 2013; Hinkel et al., 2014). Amongst these are:

- The preparation of the 2010 State of Environment Report by the European Environment Agency (EEA).
- Costs of Adaptation to Rising Coastal Water Levels for People's Republic of China, Japan and the Republic of Korea, funded by the Asian Development Bank.
- Economics of Adaptation to Climate Change (EACC): Aggregate Track Infrastructure – Coastal Component, funded by the World Bank. The project developed a global estimate of adaptation costs for informing climate negotiations and adaptation decision making.
- Economic Analysis of Coastal Adaptation to Climate Change in Senegal and Gambia, funded by the World Bank. The project assessed coastal impacts, vulnerability and adaptation using the DIVA Model for Senegal and The Gambia.
- CLIMATECOST (the Full Cost of Climate Change), funded by European Commission's DG Research under the 7th Framework Programme. The project is a study of the economics of climate change to inform policy on long-term targets, the economic costs of inaction, and the costs and benefits of adaptation. The project is quantifying the costs of climate change impacts, as compared with the costs and benefits of adaptation.
- IMPACT2C (Quantifying projected impacts under 2 degree C warming), funded by European Commission's DG Research under the 7th Framework Programme.
- PESETA Project Europe: Estimation of the costs of climate change in Europe.
- BRANCH Project: Assessment of the role of climate change in European spatial planning.

For this project DIVA has been downscaled to be applicable at scales required in order to produce information useful for developing national ICZM strategies. To this end, coastal data is represented in more detail and considering the specific geographical and socio-economical context.

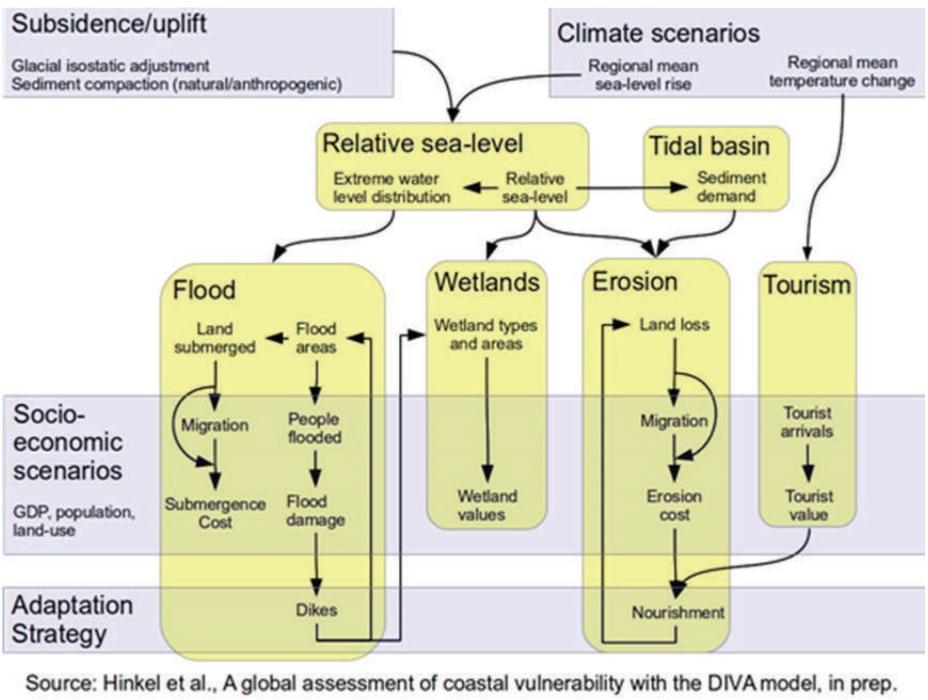

Figure 1: DIVA model structure. The yellow boxes show the various modules of DIVA and the grey boxes show the external data and scenario inputs.

2 Methods and Data

2.1 Coastal data and coastline segmentation

2.1.1 Overview

Based on the concept of linear representation of the coastline, DIVA employs a model of coastal space where geographic information is represented as a collection of geographic features and is referenced to coastal segments of variable length. Given the linear nature of the coast, all the data in the DIVA database are expressed as attributes of seven principal geographic features, namely coastline segments, administrative units, countries, rivers, tidal basins and world heritage sites; and are all referenced to linear coastal segments which have resulted from the process of the coastline segmentation. Coastal space in DIVA has been structured to represent a meaningful expression of the spatial variability in vulnerability at the national to global scales. As variations in vulnerability within the coastal zone are controlled by primary variations in the human and physical coastal interchange, several critical parameters were employed for the segmentation of the coastline. These parameters are:

(i) administrative boundaries;

(ii) the geomorphic structure of the coastal environment;

(iii) the expected morphological development of the coast given sea- level rise; and

(iv) population density.

The segmentation of the coastline is therefore used as a means to provide a series of spatial reference units for the modelling tool of the project and to link it to the geographical database. The theoretical framework underlying the segmentation is analytically described in McFadden et al. (2007).

The segments constitute the final reference units for the DIVA model (Figure 2). All the attribute data are referenced to these segments with the use of Geographic Information Systems (GIS) and spatial processing methods that are described in Vafeidis et al. (2005). For downscaling DIVA for the national-scale assessments in Croatia and Tunisia we have developed a more detailed segmentation of the coastline and updated the DIVA database using, where possible, new and improved (in terms of resolution, accuracy, spatial coverage) spatial datasets on physical and socio-economic parameters as well as local and national datasets provided by the national organisations of the countries involved. The downscaling of DIVA involved a series of steps, which are described in the following sections.

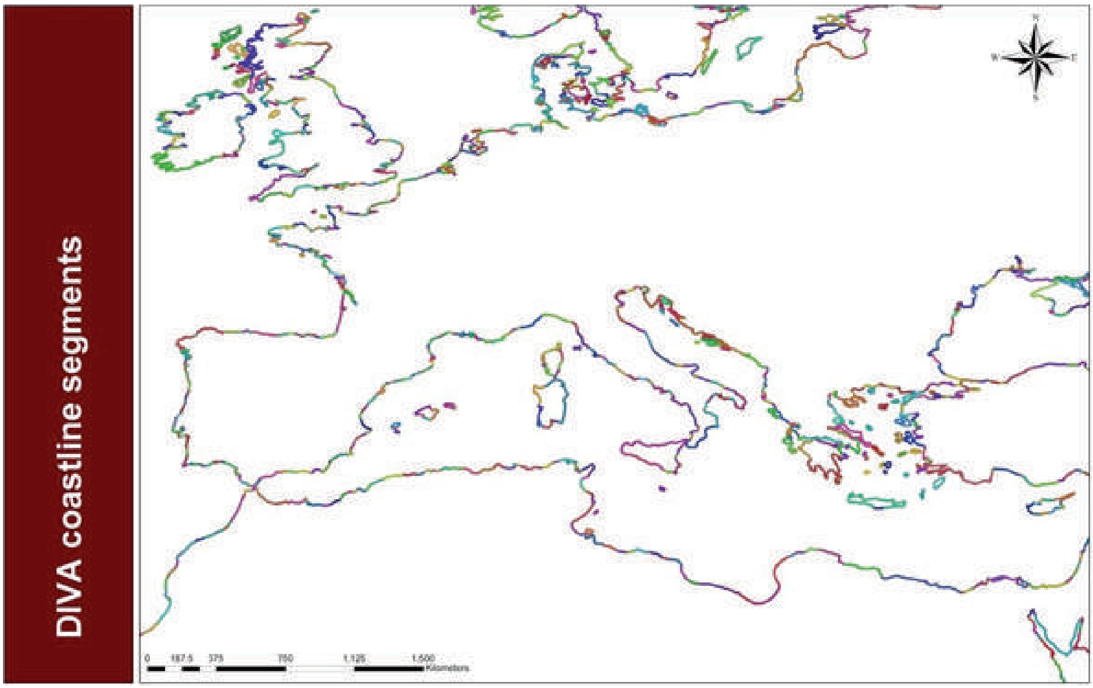

Figure 2: View of the coastline segments within DIVA for the Mediterranean basin.

2.1.2 Selection of digital coastline

The DIVA segmentation described above is based on a digital global coastline dataset (ESRI, 2002), with a scale of approximately 1:3,000,000. This scale involves a generalised, to a large degree, representation of coastline characteristics and was deemed inadequate for the purposes of a national scale assessment due to the loss of important coastal features (e.g. islands, enclosed bays, pocket beaches, etc.) of the countries. For this purpose, after comparing a series of available digital coastline datasets, we selected the Global Administrative Areas (GADM) level 01 coastline (http://gadm.org). The coastline was corrected using a smoothing algorithm (polynomial approximation) and a tolerance of 100 m in order to remove artefacts related to the format of source data (e.g. "pixelisation" of coastal segments). See Figure 3 for a comparison between the old and new coastlines for Croatia.

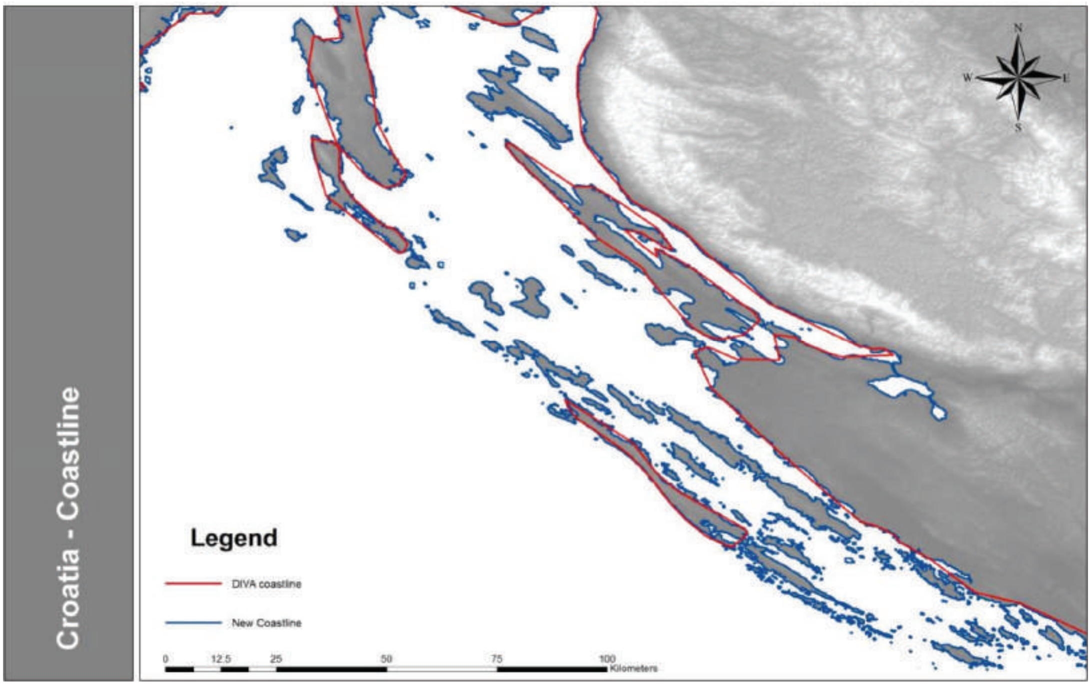

Figure 3: Comparison of global and new DIVA coastline.

2.1.3 Coastline segmentation

The coastline segmentation was based on the use of the criteria discussed in McFadden et al. (2007), namely coastal morphology and geological characteristics; population density; administrative boundaries; and extended those criteria to also include river mouths. The availability of consistent datasets on coastal morphology and characteristics is a common limitation for global-, regional- and national-scale assessments. Although the DIVA database includes global information on coastal morphology and geological characteristics (see Vafeidis et al., 2008), for the purposes of this study we developed a new dataset on coastal morphology for the entire coastline of Croatia. This dataset was based on visual interpretation of Google Earth imagery following the concepts described in Scheffers et al. (2012), also taking into account information included in the DIVA database and using location-tagged photographs from the web-service Panoramio (http://www.panoramio.com). Panoramio offers geographically tagged photographs from users for the entire coastline of Croatia, which can provide useful information on coastal type and morphology. These were used to complement/ validate the satellite imagery and the cartographical information that was available, namely the geomorphic structure developed by McGill (1958). Further, a dataset on the location of beaches, obtained from "Bathing water quality" database of Ministry of Environmental and Nature Protection, was employed for validation. The Google Earth imagery was further employed for the identification of the boundaries of river mouths.

For population density, all Croatian cities with population exceeding 10,000 people (http://population.mongabay.com/population/croatia?page=1) were considered (with the additional of some smaller ones). By combining this information with Google Earth imagery we thereby developed a new spatial dataset of the extent of coastal settlements, which was in turn used for segmenting the coastline. Finally, a digital spatial dataset containing Digital Terrain Model (DTM) and administrative boundaries for Croatia was provided by the State Geodetic Administration of Croatia.

The above information was combined to realise the segmentation of the Croatian coastline, producing a series of linear units of variable length that represent homogeneous, in terms of response to SLR, sections of the coast. Manual corrections were applied to eliminate segments with a length smaller than 100 m, as these were deemed too small for the scale of this analysis. The segmentation resulted in 1,560 segments (see Table 1), with an average length of 3.73 km (minimum length was 100.2 metres, maximum length was 116.54 km).

Table 1: Comparison of the old (global) and new (local) coastline for Croatia.

	Global DIVA coastline	New DIVA coastline
Number of segments	12	1,560
Coastline length	2,262 km	5,821 km
Segments that represent erodible beaches	0	189
Length of erodible segments	0	80.9 km

2.1.4 Exposure data – area, population and assets

Exposure of areas to inundation was assessed on the basis of the Shuttle Radar Terrain Mission (SRTM) Digital Elevation Model (DEM) (Rabus et al., 2003) according to the following series of steps: first, we identified land areas at different elevation increments (1 m, 2 m, 3 m, ...,16 m) that were hydrologically connected to the sea. In a second step, we produced buffer zones (with a width of approximately 200 km, which ensured that all hydrologically connected areas were included in the zones), to define inland areas corresponding to the coastline segments; and third, we calculated the extent of areas per elevation step within these zones. It must be noted that the zones were also extended seawards to account for mismatches between the elevation model and the coastline. The calculated area values were then assigned as attributes to the coastal segments. Further to the SRTM elevation data, information on elevation, in the form of point measurements and breaklines, was provided by the State Geodetic Administration. This information required a large amount of

processing to be converted into a form suitable for inundation modelling, which could not be conducted within the framework of this project due to lack of time, resources and adequate meta-data information (e.g. information on reference surfaces, accuracy measures of location and elevation, scale, etc.). Nevertheless, the supplied information was used to develop preliminary Triangulated Irregular Network (TIN) models of ground elevation and subsequent elevation models. A comparison of those preliminary models with the SRTM DEM showed very good agreement between the two datasets, with differences in exposure of up to 6% of the total exposed area, depending on the resolution of the developed datasets and on the exposure increment. These results suggest that SRTM elevation data provide a reliable representation of exposure for the study area.

Exposure of population was attained by summarising population per elevation increment, per coastline segment, and the resulting values were stored as attributes to the respective segments. We employed the GRUMP (CIESIN, 2004) dataset of population distribution (year 2000) and calculated the number of people per elevation increment by combining this information with the elevation data. Values were stored as attributes to the coastline segments.

Exposure of assets per elevation was assessed using the same method as for population: assets were summarised per elevation increment, per coastline segment, and the resulting values were stored as attributes to the respective segments. The spatial assets dataset was, however, produced differently from previous assessments. Large area coastal flood impact assessments usually assess the value of exposed assets by multiplying population, GDP-*per-capita* and empirically attained assets-to-GDP-*per-capita* ratios (e.g. Green et al., 2011; Hallegatte et al., 2013). This is also the approach earlier DIVA assessments have taken. For Croatia a different approach was necessary in order to take into account higher assets-to-GDP-*per-capita* ratios in the Mediterranean due to substantial tourism-related secondary housing. Spatial distributions of the economic values of assets were thus derived independently from population data for each municipality/town as described in Pascual and Markandya (2014) and in Appendix A.

The digital datasets employed for the assessment of exposure and their characteristics are shown in Table 2.

Table 2: The digital datasets used to assess exposure of population and assets.

Dataset	Reference
SRTM 90 m Digital Elevation Data (3 arc seconds)	CGIAR-CSI (Consultative Group for International Agriculture Research – Consortium for Spatial Information). Jarvis A., H.I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from http://srtm.csi.cgiar.org. (accessed 18.12.2013).
GRUMP (Population count grid, 30 arc seconds, population year 2000)	CIESIN (Center for International Earth Science Information Network), Columbia University; International Food Policy Research Institute (IPFRI); the World Bank; and *Centro Internacional de Agricultura Tropical* (CIAT); 2004. Global Rural-Urban Mapping Project (GRUMP): Urban/Rural Population grids. Palisades, NY: CIESIN, Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw
Assets layer	Pascual, M. and Markandya, A. (2015): Estimation of values of housing and tourism facilities along Croatian coast. Working Report as an Input to the Climate Variability Project. See Appendix A.

2.1.5 Erosion parameters

We utilised the dataset on coastal morphology that was developed during the segmentation process in order to characterise the degree of erodibility of the different coastal types and to calculate the parameters for the erosion algorithm of DIVA. We implemented a slightly modified version of the method that was used in the global DIVA database (see Vafeidis et al., 2005) in order to assign new Erosion Factor values to all segments representing erodible coastal types. Based on expert judgement a value of 1 (i.e. 100% erodible) was assigned to segments that represented erodible beaches (i.e. primarily consisting of erodible material such as sand, granular gravel, or combinations of those with stones or pebbles) while a value of 0.3 was assigned to segments that consisted of rocky coasts with pocket beaches. 181 beaches with a total length of approximately 80 km were identified as erodible (Figure 4). Most of these beaches (over 90%) were included in the "Bathing water quality" database of the Ministry of Environmental and Nature Protection which depicted 653 beaches of all types (with no information however on beach material). Rocky and urban coasts were considered to be non-erodible and were assigned a value of zero. Erosion damages to quays and other elements of the built environment are not considered here, because they are too detailed in order to be resolved here.

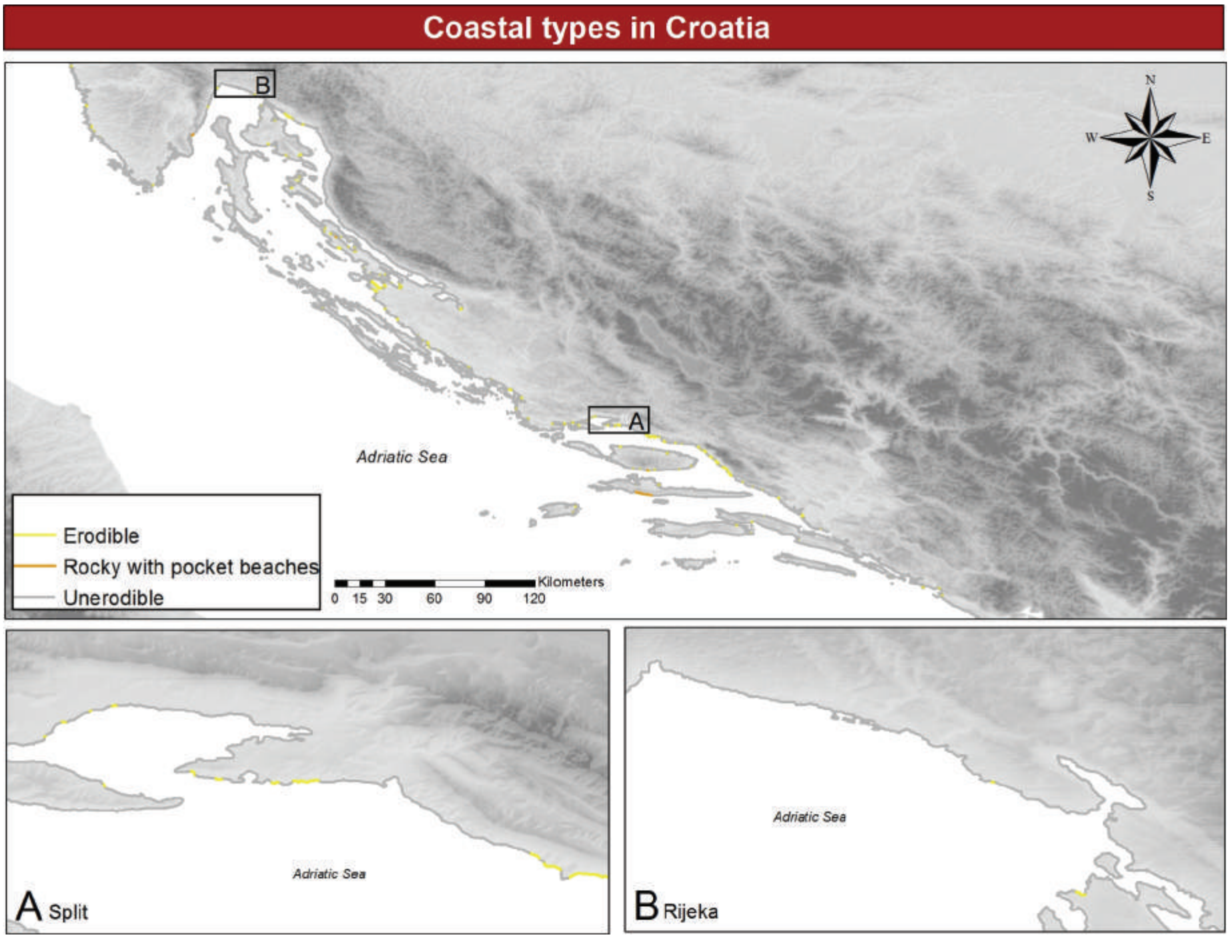

Figure 4: Coastal types in Croatia.

2.2 Sea-level rise scenarios

The generation of regional sea-level rise scenarios follows the methodology of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). For each concentration scenario, we constructed regional sea-level rise scenarios. These results are based on scenarios developed in the Inter-Sectoral Impact Model Intercomparison Project Fast Track funded by the

German Federal Ministry of Education and Research as published in Hinkel et al. (2014). These scenarios take into account a wider range of ice melting uncertainty than in AR5, which leads to slightly higher sea levels as compared to AR5. These scenarios are better suited for adaptation assessments than the IPCC scenarios, because according to the IPCC assessment there is a 0–33% probability that the global mean sea-level rise lies outside of the IPCC range (Hinkel et al., 2014). AR5 estimates that global mean sea-level is likely to rise up to 0.98 m from 1986–2005 to 2100 under the highest greenhouse gas concentration scenario considered (RCP 8.5, roughly a "4 to 5 degree world" when a mid-range transient climate response is considered; Church et al., 2013). The highest estimate used in this report for the same concentration scenario and the same time period was 1.10 m (Table 3). The following four components of climate-induced sea level were considered:

- The steric contribution for the sea-level rise projections are taken for HadGEM2-ES (Collins et al., 2008) from the CMIP5 archive.
- The contribution of glaciers and ice caps to global mean sea-level rise was taken from Marzeion et al. (2012). They model the past and future mass balance of all glaciers contained in the Randolph Glacier Inventory based on air temperature and precipitation anomalies obtained from the CMIP5 climate models, added to the observed climatologies of New et al. (2002).
- The sea-level rise estimations coming from mass changes of the Greenland Ice Sheet (GrIS) and peripheral ice caps are based on surface mass balance (SMB) estimates from Fettweis et al. (2012), extended to more CMIP5 models and augmented by +20 ± 20% to account for missing dynamic processes (see Hinkel et al., 2014).
- Antarctic sea-level projections are obtained through five continental ice sheet models driven by global mean temperature change of 19 climate models. In order to obtain a probability distribution, switch-on experiments within the SeaRISE project are combined with linear-response theory. Here we use the 5%, 50% and 95% quantiles as reported in Levermann et al. (2012).

We created a low, medium and high land-ice scenario by summing up the three land-ice components along percentiles (5^{th}, 50^{th}, 95^{th}) to create a "very likely" range. The overestimate of the total uncertainty – in comparison to using root mean square – is only marginal since most of the uncertainty comes from the Antarctic ice sheet. Global-mean sea-level change contributions from Greenland and Antarctic ice sheets are then combined with their gravitational-rotational fingerprints in order to obtain the regional contributions. We considered uniform mass loss over the ice sheets, using the same model as Bamber and Rive (2010). The fingerprints also include instantaneous, local land uplift in the vicinity of the ice sheets due to the elastic response of the solid Earth upon melting (not to be mistaken with long-term glacial-isostatic adjustment described below), thus also describing relative sea level changes. A uniform pattern is assumed for mountain glaciers and ice caps. Table 3 shows the results for the four components, Figure 5 shows the global mean sea-level rise scenarios used here.

For the study on Croatia we used three sea-level rise scenarios. One lower bound scenario (RCP 2.6 combined with the 5% quantile of ice-melting projections), called *low SLR* below, one medium scenario (RCP 4.5 combined with the median), called *medium SLR*, and one upper bound scenario (RCP 8.5 combined with the 95% quantile), called *high SLR*.

Table 3: Global mean sea-level rise in 2100 with respect to 1985-2005.

Scenario	Model	Steric [cm]	Land-ice [cm]				Total [cm]
			Glacier	Antarctica	Greenland	Sum	
RCP 26	HadGEM2-ES	14	14 (14.15)	7 (2.23)	0 (0.0)	21 (16.39)	35 (29.52)
RCP 45	HadGEM2-ES	18	17 (16.19)	8 (2.29)	7 (5.8)	32 (23.56)	50 (41.75)
RCP 85	HadGEM2-ES	29	22 (20.26)	10 (2.41)	12 (10.14)	44 (31.81)	72 (60.110)

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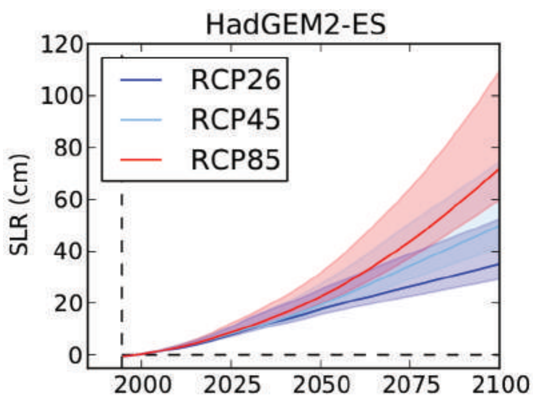

Figure 5: Global mean sea-level rise under the scenarios used here.

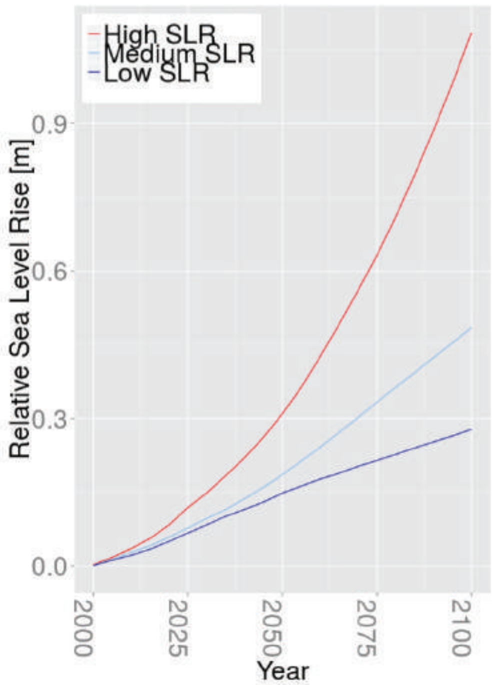

Figure 6: The average sea-level rise for Croatia for the three scenarios we used.

We also accounted for local vertical land movement due to glacial-isostatic adjustment (resulting from loading and unloading of the ice sheets during the last Ice Age) after Peltier (2000b). Natural (e.g., due to sediment compaction in river deltas) and enhanced human-induced subsidence (e.g., due to ground fluid abstraction or drainage) is not considered due to high spatial variability of this factor and also the lack of consistent observations or future scenarios. These omitted factors are, however, expected to have only a very small contribution to relative sea-level rise in Croatia. Glacial-isostatic adjustment contributes with a rise of land (and thus falling sea level) with a rate of 0.15 mm/year (in the north of Croatia) to 0.12 mm/year (in the south). These 1.2–1.5 cm of falling sea-level over 100 years are a rather small contribution to the total sea-level rise shown in Figure 6.

In particular, we get the values of sea-level rise in 2050 and 2100 presented in Table 4.

Table 4: Sea-level rise in Croatia in 2050 and 2100 under the three sea-level rise scenarios we use.

Scenario	Sea-level rise Croatia, 2050	Sea-level rise Croatia, 2100
Low SLR	0.15 m	0.28 m
Medium SLR	0.19 m	0.49 m
High SLR	0.31 m	1.08 m

2.3 Extreme water levels

Information on extreme water levels for different return periods are included in the DIVA database. For Croatia, further information was provided by the Hydrographic Institute of the Republic of Croatia (2012) for specific locations along the Croatian coast. This information referred to seven stations/tide gauges along the Croatian coastline and was used to evaluate the global DIVA data. The two datasets were overall in good agreement, with differences being in the range of 0–8 cm, which is lower than differences related to methodological uncertainties in the calculation of surge heights for different return periods (Arns et al., 2014). Nevertheless deviations (up to 20 cm), still within the range of methodological uncertainty, existed in specific locations (e.g. Split). Also in those cases, global DIVA values were utilised as these included consistent values for the entire Croatian coast. Interpolating the tide-gauge location data to generate values in space (spatial interpolation) is a complex process (Eastoe et al., 2013) which would require work that would be beyond the scope of our analysis.

Extreme water levels are displaced upwards with the rising sea level, as there is no clear evidence that climate change will further alter the distributions. Analysis of global tide gauge datasets shows an increase in extreme high water levels since 1970 worldwide, but also shows that mean sea-level rise is the major factor for this increase (Menéndez and Woodworth, 2010).

Table 5 shows the extreme water levels used in the assessment of flood exposure and risk for Croatia (average values over all coastline segments). H1 is the water level that is exceeded on average once every year and H100 is the water level exceeded on average once every 100 years (thus having a probability of 1% to be exceeded in a particular year). While in 2010 H1 is about 0.83 m and H100 is about 1.14 m these values go up with sea-level rise. H100, for example, will be 2.20 m under RCP 8.5 in 2100.

Table 5: H1 and H100 in 2010, 2050 and 2100 under different SLR scenarios.

Scenario	H1, 2010	H1, 2050	H1, 2100	H100, 2010	H100, 2050	H100, 2100
Low SLR	0.83 m	0.95 m	1.08 m	1.14 m	1.26 m	1.39 m
Medium SLR	0.84 m	0.99 m	1.29 m	1.14 m	1.30 m	1.60 m
High SLR	0.84 m	1.12 m	1.89 m	1.15 m	1.43 m	2.20 m

2.4 Socio-economic scenarios

One of the most important drivers of coastal climate change and climate variability impacts is Socio-Economic Development (SED). SED determines how many assets and people will be located in the coastal zone and thus be at risk of experiencing coastal impacts. Future Socio-Economic Development cannot be predicted but must be explored through the use of socio-economic scenarios.

Here we use the state-of-the-art socio-economic scenarios in the form of five population and gross domestic product (GDP) growth scenarios based on the Shared Socio-economic Pathways (SSP 1–5; Arnell et al., 2011; O'Neil et al., 2011). Each SSP represents different assumptions about future global and national development. See Table 6 for global GDP and population in 2050 and 2100 and Figure 7 for national level estimates for Croatia.

The highest GDP and lowest population numbers are attained under SSP1 (called "Sustainability"), which reflects a world progressing towards sustainability with reduced resource intensity and fossil fuel dependency, and SSP5 (called "Conventional Development"), which reflects a world oriented toward equitable rapid fossil fuel dominated development. GDP is lowest and population highest under SSP3 ("Fragmentation"), which reflects a world fragmented into poor regions with low resource intensity and moderately healthy regions with a high fossil fuel dependency. GDP and population under SSP4 (Inequality), which is a highly unequal world both within and across countries, follow a similar but less extreme trend as compared to SSP3. SSP2 (Middle of the Road) reflects a world with medium assumptions between the other four SSPs.

Table 6: Global population and GDP in 2050 under different SSPs.

	Population (in millions)		GDP (billion US$/y)	
SSP	2050	2100	2050	2100
SSP1	8,400	7,200	295,000	771,000
SSP2	9,300	9,800	260,000	685,000
SSP3	10,300	14,100	169,000	355,000
SSP4	9,400	11,800	242,000	462,000
SSP5	8,500	7,790	348,000	1,207,000

For this analysis we focus on the SSP2, SSP3 and SSP5, as these three scenarios sufficiently span the full uncertainty space. The respective growth rates are applied to the population and assets exposure data. These scenarios cover a similar range to the scenario from the national statistical projections (Grizelj and Akrap, 2011). SSP2 is almost identical to the Scenario 2 of these national figures. To be consistent with previous studies and the Croatian assets projections generated by Pascual and Markandya (2015), we stick with the SSP Scenarios in this report. The population and GDP *per capita* for Croatia are shown in Figure 7.

For Croatia we have a falling population in all scenarios. In SSP3 the falling trend end around 2070 and the population stabilises around 4.0 million people. In the other SSPs the population continues to fall throughout the century and down to below 3 million in 2100 for SSP5. The GDP *per capita* grows in all scenarios reaching between US$ 48,490 and US$ 106,670 in 2100. Table 7 summarises population and GDP *per capita* in 2050 and 2100 for the SSPs used in this study.

Table 7: Croatian population and GDP per capita in 2050 under different SSPs.

	Population in Croatia [Million]		GDP *per capita* (Croatia) [US$]	
Scenario	**2050**	**2100**	**2050**	**2100**
SSP2	4.06	3.22	31,320	58,380
SSP3	4.04	3.96	28,970	48,490
SSP5	4.09	2.66	37,980	106,670

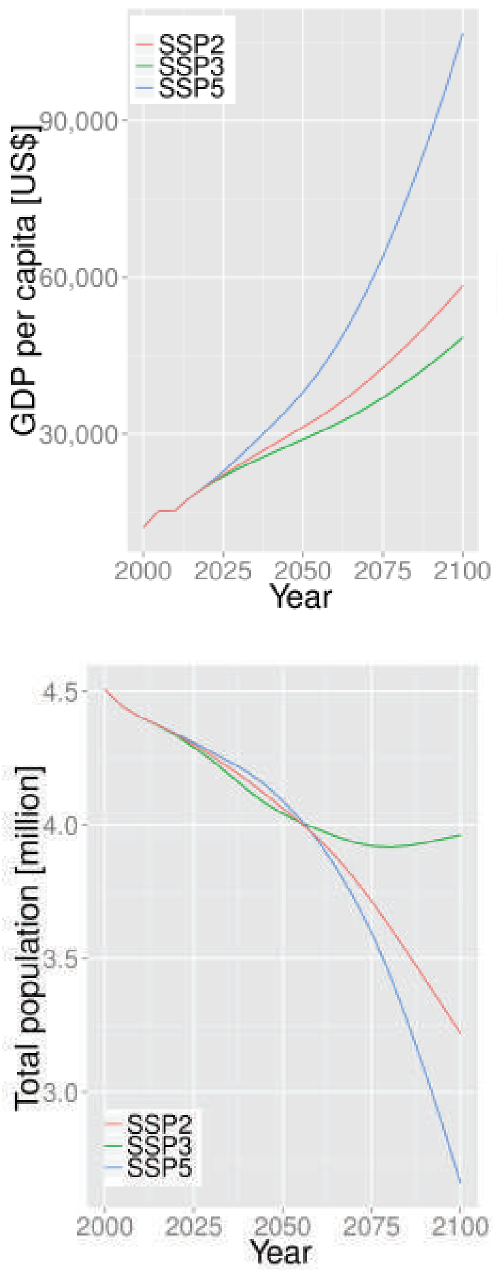

Figure 7: Population and GDP per capita in Croatia under the three SSP scenarios used.

2.5 Assessment of erosion impacts

The impacts of sea-level rise in terms of increased erosion of sandy beaches are assessed following Hinkel et al. (2013a) in terms of the following three metrics:

- **Land loss**: annual loss of land [km²/yr];
- **Migration cost**: annual costs of forced migration due to land loss [million US$/yr];
- **Nourishment cost**: annual cost of replacing eroded sand through beach or shore nourishment [Million US$/yr].

Beach erosion can occur at a range of time-scales (Stive et al., 2002, 2009). Individual storms will generally lead to rapid short-term erosion, followed by rapid short-term accretion and the net change is often negligible. If sediment deficiencies persist, more chronic long-term erosion can result. This paper addresses such chronic long-term erosion due to sea-level rise. Erosion is computed following Hinkel et al. (2013a). This approach first computes horizontal recession rates based on the Bruun (1962) rule, which describes how an equilibrium profile responds to relative sea-level rise in a two-dimensional sense. It considers near-shore slope and material composition and can be used to compute the total area lost due to direct erosion.

The horizontal recession rates obtained are then translated into the loss of sand volume using the length and the active beach profile height. The beach length is computed as explained in Section 2.1.6. The active profile height is the zone that responds to sea-level rise and thus is the sum of the coastal elevation above high tide (B), the depth of closure due to wave climate (D) and the tidal range (H). B is assumed to be 2 m in all calculations, following a typical value. D is estimated through wave climate data. Repetitive beach profiles show an empirical relationship between the depth of closure and the wave climate (Hallermeier, 1981; Nicholls, 1998) and this concept is widely applied in coastline change models (e.g., Ashton et al., 2001). Wave heights are taken from the LOICZ coastal typology (Maxwell and Buddemeier, 2002) and used as indicative of an annual extreme wave height. Following Hallermeier (1981), the depth of closure is approximately twice this height. Tidal range data is also taken from the LOICZ typology. See also Hinkel et al. (2013a) and Vafeidis et al. (2008).

Two main socio-economic impacts of erosion are evaluated: dryland loss and forced migration of the people living there. Dryland loss refers to the loss of habitable land. The dominant land-use class per segment taken from the IMAGE Model (IMAGE Team, 2002) is used to value these losses. Generally, this is agricultural or lower value land classes (e.g., nature areas, forests or tundra). In these cases, it is assumed that should land for more valuable uses such as housing or industry be lost due to erosion, then those activities would relocate elsewhere at the expense of the dominant agricultural or lower value land. The number of people forced to migrate is calculated as the product of the land area eroded and the average population density per segment – that is, we assume that the population is spread evenly over the area. Following Tol (1995), emigration is valued at three times *per capita* income.

Impacts are assessed both without and with adaptation in the form of beach and shore nourishment, i.e. the replacement of eroded sand (Dean, 2002). In beach nourishment, the sand is placed directly on the intertidal beach, while in shore nourishment the sand is placed below low tide where the sand will progressively feed onshore due to wave action, following current Dutch practice (van Koningsveld et al., 2008). Shore nourishment is cheaper than beach nourishment and effective in slowing erosion, but it is less effective at sustaining the attractiveness of a beach for tourism, because the benefits on the dry beach are not felt immediately. Based on information of Deltares, we assume the unit cost of beach nourishment to be US$ 6/m^3 and of shore nourishment US$ 3/m^3.

Nourishment is applied following a cost-benefit analysis considering the damage avoided in terms of land loss, forced migration and tourism. Because both the costs and benefits are assumed to be linear functions of the amount of nourishment, segments are either fully protected (so that no damage is done) or not at all. For areas with coastal tourism, beach nourishment is the preferred adaptation option. It is applied if the combined benefits in terms of land loss, migration and tourism are sufficient. If the costs of beach nourishment cannot be justified by its benefits, then shore nourishment is evaluated to avoid land loss and forced migration. The level of tourism and tourism revenues are calculated using the Hamburg Tourism Model (HTM) (version 1), which is an econometric model of international tourism flows at a national scale (Hamilton et al., 2005a; 2005b).

2.6 Assessment of flood damage and sea-level rise impacts

Potential coastal flood damage and sea-level rise impacts are assessed following Hinkel et al. (2014) in terms of the following metrics: All elevations are reported relative to mean sea-level (MSL):

- **Area below H100 (potential floodplain)**: the area below the 1-in-100 year extreme water level [km^2].
- **People below H100**: the number of people living below the 1-in-100 year extreme water level.
- **Assets below H100**: The value of assets below the 1-in-100 year extreme water level [billion US$].
- **People flooded**: the average number of people flooded annually through extreme water level events [people/yr].
- **Flood cost**: The average annual damage caused by coastal flooding [billion US$/yr].
- **Dike height [m]:** The dike height relative to MSL.

- **Adaptation cost**: The annual cost of maintaining and upgrading coastal defences [billion US$/yr].

For each coastline segment, a cumulative people exposure function that gives the number of people living below a given elevation level x is constructed by superimposing a DEM with a spatial population dataset and interpolating piecewise linearly between the given data points. Only population of grid cells that are hydrologically connected to the coast are considered. Also for each segment, a cumulative asset exposure function is attained by superimposing the DEM with a spatial assets dataset produced within the project (see also 2.1.4 for a description of this exposure data). Future exposure is attained by applying national population and GDP growth rates of the socio-economic scenarios.

For people we only make the binary distinction between flooded and not flooded, which means that the damage function is identical to the cumulative exposure function. For assets, the damage also depends on the depth by which the asset is submerged. Following Messner (2007), we assume a relative depth-damage function (a function that gives the fraction of assets damaged for a given flood depth) that is in flood depth with a 1-meter flood destroying 50% of the assets. This function has a declining slope, reflecting that each unit increase in water depth produces less and less damage. The selection of 1-m depth is a good indicative value based on the available information. The damage to assets done by a flood of height x is computed by integrating from elevation level 0 to x over the product of the depth-damage function applied to the water depth (x−y) and the derivative of the cumulative exposure function applied to the elevation level y.

In the case that there are dikes, we assume that the damage is zero for floods with a height below the dike height. Dikes are built following an econometrically derived demand function for safety which is increasing in *per capita* income and population density and was taken from Hinkel et al. (2014). This function estimates a coastal societies' demand for safety in terms of the flood return period against which to protect. The flood return period is the inverse of the probability of an extreme water level being exceeded in a given year. A return period of 1-in-100 years, for example, refers to the flood height having an exceedance probability of 1% per year. Following this function, dikes are built and upgraded for each coastline segment in each time step (5 yr). An adjustable population density threshold is used to decide if a dike is built. If the population density is below the threshold, no dikes are built. For this report we used 30, 100 and 200 inhabitants/km^2 (see next chapter). It should be noted that in the DIVA model a dike can only be built completely for one segment. That means that the whole segment has to have a dike or the whole segment has to have no dike. Some of the (smaller) islands are modelled as one segment only, so for these islands there are just the two options: to protect them completely or not at all, even if the island has only one village.

Dike capital costs are computed based on the attained dike height, coastal segment length, and dike unit costs taken from Hoozemans et al. (1993), which are assumed to be constant over time and linear in dike height. Following Hanson et al. (2011), we also calculate the maintenance costs of dikes which are at 1% *per annum* of the construction costs of the dikes.

Finally, we compute the people flooded and the flood cost as mathematical expectation of the people and assets damage functions, where the probability density function of extreme water levels is derived based on extreme water levels given for different return periods in the DINAS-COAST database (Vafeidis, 2005). Future extreme levels are obtained by uniformly applying relative sea-level rise to the distribution. Hence, no changes in storm characteristics are assumed. See also Section 2.3.

3 Results

3.1 Flooding

3.1.1 Current and future exposure

This section presents results in terms of the current and future exposure to coastal flooding. Exposure to extreme water level events (i.e. storm surges) is expected to increase in the coming decades due to both rising sea-levels, which in turn raises extreme water levels; and socio-economic development. Figure 8 shows the impacts of the sea-level rise on the area extent of the 1-in-100-year flood (area below H100). Due to Croatia's long coastline, even an increase of extreme water levels of a few centimetres leads to an increase of the flood area of several square kilometres. The area below H100 is expected to rise from about 240 km² today to 310 km² in 2050 and 360 km² in 2100 under RCP 8.5.

Coastal floodplain in the Neretva River Delta area (Ploče, Opuzen and Slivno administrative units) is by far the biggest potentially flooded area. Its today's area below H100 of around 81 km^2 could grow up to around 100 km^2 in 2050, and 106 km^2 in 2100 under the high SLR scenario. This area is around eight times bigger than the second biggest floodplain area below H100, which is Zadar (see Appendix B1).

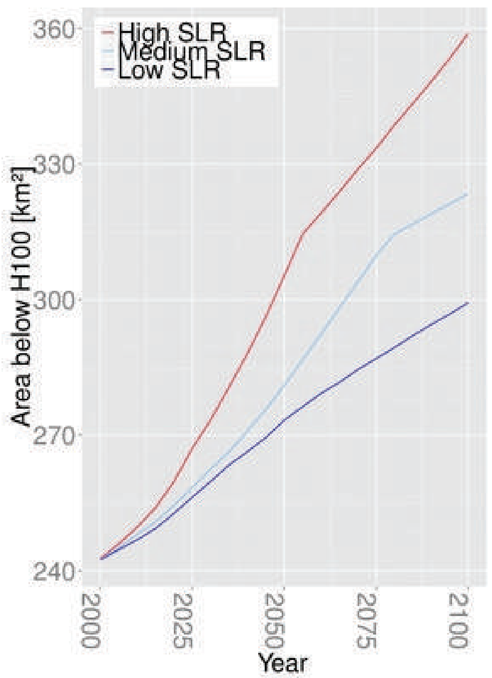

Figure 8: The potentially flooded area below H100 in Croatia until 2100.

In terms of built-up clusters[1] within major coastal cities, Pula has the largest potential flood area, where up to 2.2 km² could be flooded by a 1-in-100 year flood event in 2050, compared to the 2.0 km² of today. Other significant potential floodplains are in Zadar and Split, while in Rijeka only a small area (around 0.3 km² below H100) is potentially affected.

Figure 9 shows how the exposure of assets and people in Croatia changes under the three sea-level rise scenarios and under the three SSPs. While US$ 2.3 billion asset values are below the height of the 1-in-100-year flood today, in 2050 these values range from US$ 4.6 billion (low SLR, SSP3) to US$ 9.6 billion (high SLR, SSP5). In 2100, our projections range from US$ 7.3 billion (low SLR, SSP2) to US$ 22.3 billion (high SLR, SSP5).

Zadar area has the highest asset value in the floodplain – around US$ 210 million today. This could grow up to US$ 490 – 860 million in 2050 and US$ 1.0–2.2 billion in 2100 (see Appendix B, Table B2.1). Other potentially highly impacted areas regarding asset values are Šibenik and Kaštela Bay area (Split, Solin, Kaštela and Trogir administrative units). As for the built-up clusters within major coastal cities, Zadar has the highest asset value in the floodplain: US$ 150 million today and 310 to 690 million in 2050. This is roughly four times as much as in Pula and about five times as much as in Split and Rijeka (see Appendix B, Table B2.2). For 2100, we project US$ 510 million to US$ 1.6 billion assets below H100 for Zadar built-up cluster (see Appendix B, Table B2.4).

Population in the potential floodplain was calculated as 66,000 people today. In 2050 we project 82,000 (low SLR, SSP3) to 114,000 (high SLR, SSP5) people below H100, and in 2100 70,000 to 129,000 people are projected to live below H100.

[1] The extent of built-up area is estimated based on satellite imagery.

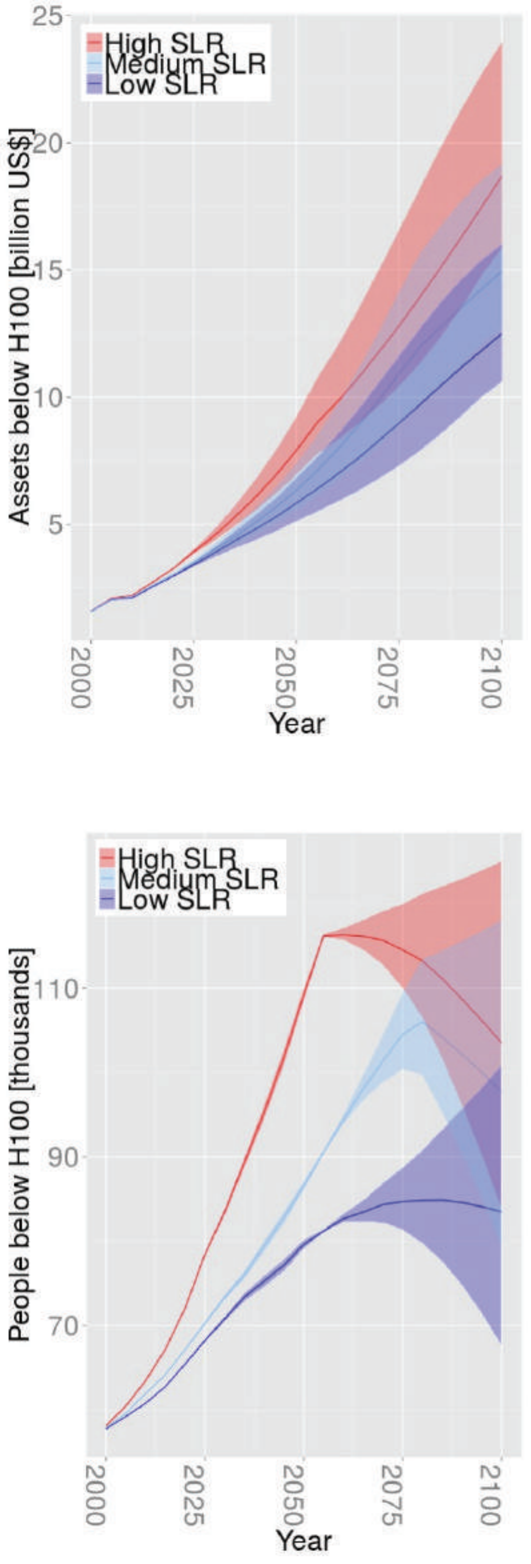

Figure 9: Assets (top) and population (bottom) below H100 in Croatia until 2100. The shaded areas show the uncertainty due to the socio-economic scenarios and the lines show the results under SSP2.

The Kaštela Bay area has the highest number of people living in the floodplain (people below H100). This number could increase from today's 10,600 to 14,000–19,600 in 2050 and 12,000–21,300 in 2100.

Looking at built-up clusters within major coastal cities, Split has the highest population living below H100, 3,500 people today, 4,600 (low SLR, SSP2) – 6,500 (high SLR, SSP5) in 2050, and 4,000 (low SLR, SSP5) – 7,200 (high SLR, SSP3) in 2100. Rijeka is roughly at the same level.

It should be noted that most of the uncertainty for the population exposure comes from SSPs. Under all three sea-level rise scenarios people below H100 in 2100 could be more or less than today, depending on the SSP population projection. This is not the case for assets, where under each sea-level rise scenario and each SSP the assets below H100 in 2100 are much higher (at least three times) than today. We further would like to point out that areas with the highest population exposure are not the ones with the highest asset exposure. Cities like Split and Rijeka have high population exposure but low asset exposure. Otherwise we have municipalities like Vodice and Novalja which have a lot of tourism infrastructure but not a high permanent population.

3.1.2 Current and future risk to people and assets

This section presents the risk of current coastal floods in terms of the number of people expected to be flooded annually and the expected annual damages to assets (building, infrastructure, etc.) as well as how this risk will increase due to sea-level rise and socio-economic development. It is important to note that risk is a statistical measure that combines information on exposure as presented in the last section with information on the hazard (here sea-floods) and vulnerability as described above. Risk measures should not be confused with actual damages of floods. Actual damages and risk measures can only be compared over long time-horizons. All results below assume that no protection measures are in place or will be built in the future.

Figure 10 shows the average number of people flooded annually under different scenarios. While today about 17,000 people are expected to be flooded annually, this number could increase up to 40,000 (low SLR), 48,000 (medium SLR), or 72,000 (high SLR) in 2050. It should be noted that until 2050 the number of people flooded depends

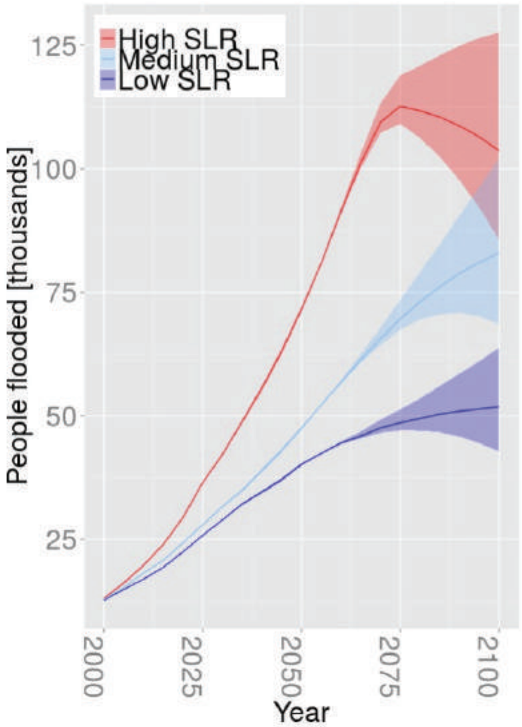

Figure 10: The average number of people flooded annually under different sea-level rise and population scenarios. The shaded areas show the uncertainty due to the socio-economic scenarios and the lines show the results under SSP2.

almost only on the sea-level rise scenario and not on the population scenario, because the population scenarios do not differ significantly before 2050. In 2100 under the low SLR scenario 43,000–64,000 people are expected to be flooded annually, under the medium SLR scenario 69,000–85,000 people are expected to be flooded annually, and under the high sea-level-rise scenario, 102,000–128,000 people are flooded annually. Annual number of people flooded in 2100 under SSP2 and the medium SLR scenario is shown in Figure 11.

Looking at local results, the Kaštela Bay area has the highest number of people at risk of being flooded annually (around 2,900 today). This number is expected to rise up to 12,400 in 2050 and up to 21,100 in 2100 under the high SLR scenario. In terms of built-up clusters within major cities (see Appendix B, Tables B3.2 and B3.4) Split and Rijeka have the highest number of people flooded. Zadar and Pula are following close.

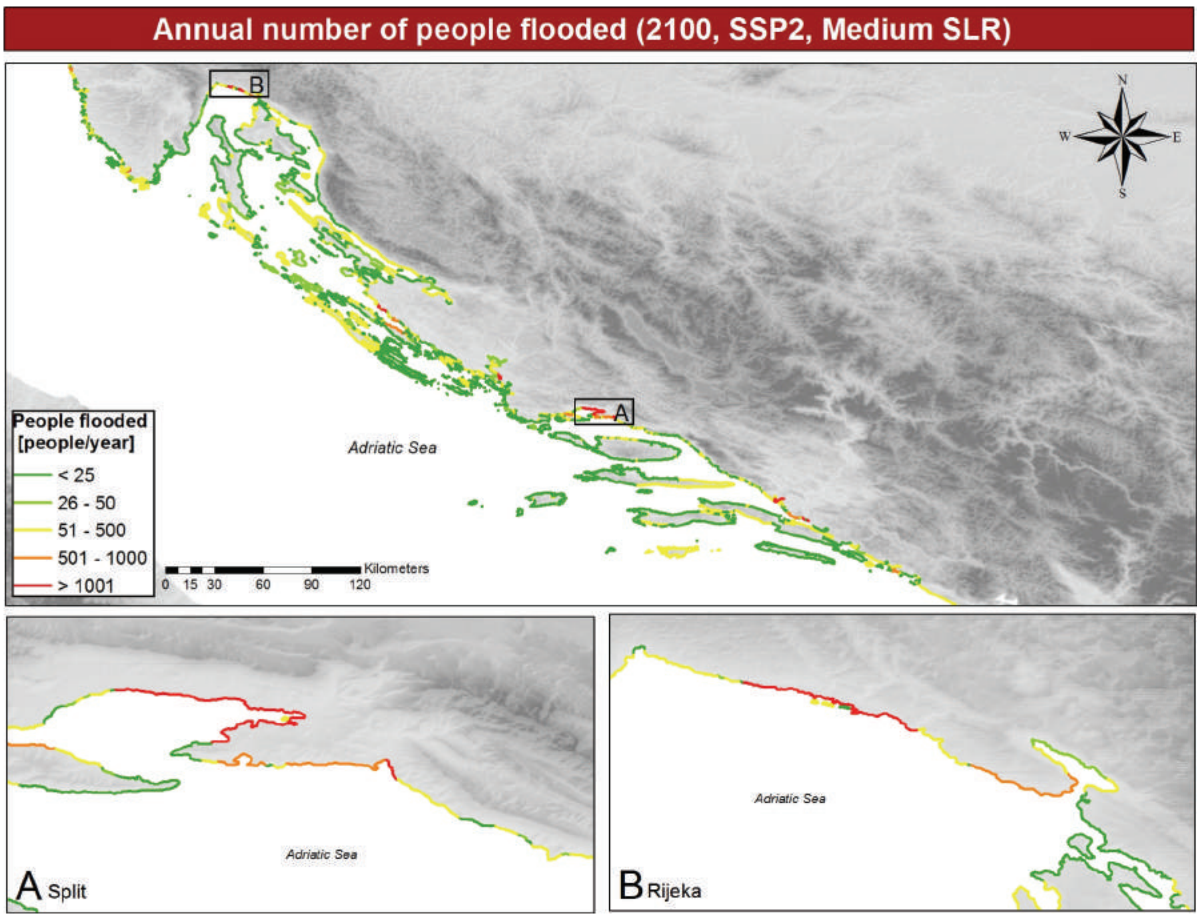

Figure 11: Annual number of people flooded in 2100 under SSP2 and the medium SLR scenario.

Figures 12 and 13 show the expected annual sea-flood cost for all of Croatia. Today the expected annual flood costs are US$ 40 million. Under the high sea-level rise scenario the annual damages by sea-floods grow up to a range from US$ 670 million to US$ 880 million in 2050, and in 2100 we project US$ 5.9 billion to US$ 8.9 billion average annual damages by sea-floods. Under the low sea-level rise scenario the expected damages are much lower, ranging from US$ 240 million to US$ 320 million in 2050 and from US$ 0.9 billion to US$ 1.4 billion in 2100.

On local level Zadar, Šibenik and Kaštela Bay are the areas subjected to the highest expected damages from sea-floods. Today the area of Zadar could expect sea-flood costs of US$ 3.6 million, which grow to a range from US$ 23 to 31 million under the low SLR scenario, and to a range from US$ 63 to 83 million under the high SLR scenario in 2050. By the end of the century, the same area is expecting sea-flood costs in the range from US$ 86 to 130 million for the low SLR scenario and in the range from US$ 540 to 820 million in the high SLR scenario. Šibenik is following closely, with expected sea-flood costs of approximately 90 percent of the ones in Zadar (see Appendix B, Tables B4.1 and B4.3). Regarding built-up clusters within major coastal cities, Zadar is the most affected. While today's average annual damages by sea-floods are computed as US$ 2.6 million, in 2050 the expected damage ranges from US$ 17 million to US$ 62 million. In 2100 the projected range of sea-flood cost in Zadar is US$ 64 million to US$ 630 million, depending on the sea-level rise scenario and the SSP. Pula, Split and Rijeka are far less affected experiencing damages that are five to six times lower than the ones in Zadar (see Appendix B, Tables B4.2 and B 4.4).

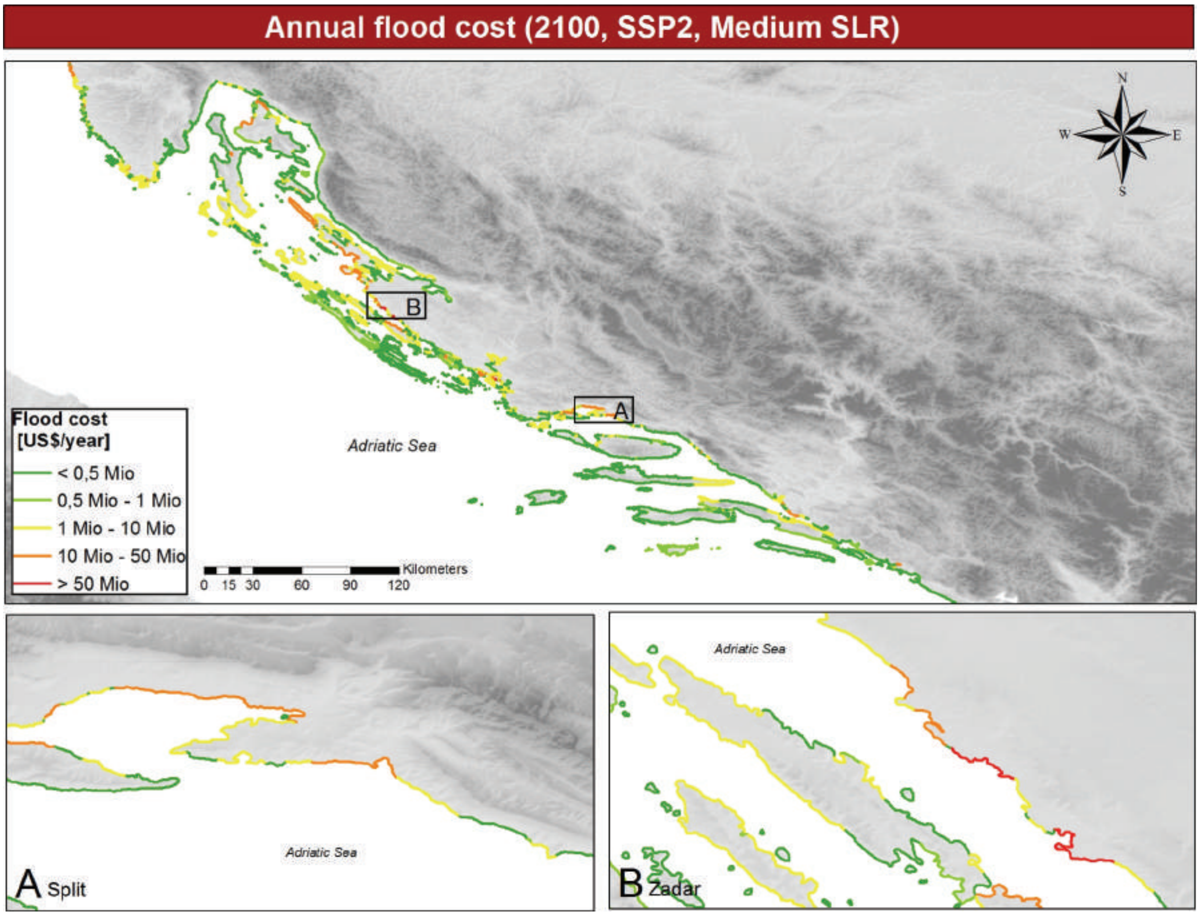

Figure 12: Expected annual flood cost under SSP2 and Medium SLR scenario in Croatia in 2100.

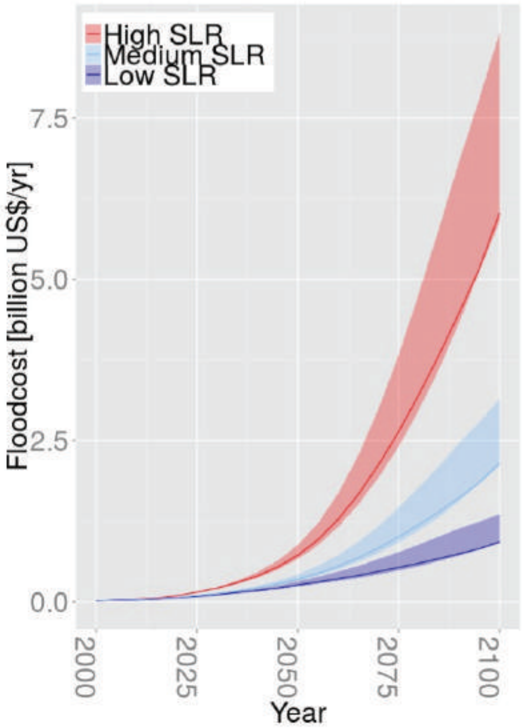

Figure 13: Expected sea-flood cost in Croatia under different sea-level rise scenarios until 2100. The shaded areas show the uncertainty due to the socio-economic scenarios and the lines show the results under SSP2.

3.1.3 Risk to World Heritage Sites

Using the list of UNESCO World Heritage Sites (http://whc.unesco.org/en/list/) we identified six coastal sites that are lying in the Croatian Low Elevation Coastal Zone (LECZ) – see McGranahan et al., 2007. This was based on the visual correction of the latitude/longitude co-ordinates reported at the UNESCO site, with the use of Google Earth. A site was characterised as exposed when it lied (even partially) below 10 m elevation. Information on the selected sites is shown in Table 8.

Under current conditions, both the Cathedral of St James in Šibenik and Episcopal Complex of Euphrasian Basilica in Poreč lie below the 100-year surge and thus are at risk under current climate variability. The Episcopal Complex of Euphrasian Basilica in Poreč is particularly vulnerable, since it is located directly at the coast at 0 m elevation considering mean sea level (Figure 14; Table 8). Although at first the other sites do not appear to be at immediate risk of flooding today and in the near future, elevation data from the Croatian Base Map (State Geodetic Administration of Croatia, http://geoportal.dgu.hr) show that this high exposure also applies to other UNESCO sites. This relates primarily to Stari Grad Field, the historic centre of Trogir and Diocletian's palace in Split. It should be noted that some parts of the Diocletian palace (the cellars, to be more accurate) are below mean sea level even today. In addition, according to SRTM data five out of these six sites will be at risk to coastal flooding towards the end of the century under the high SLR scenario when the 1-in-100-year flood level is estimated to reach 2.2 m (see Table 8). This needs to be confirmed by further, more detailed, analysis, which will consider uncertainties in elevation as well as local hydro- and geo-morphological and surge characteristics.

Table 8: Information on Croatian World Heritage Sites that are exposed to.

Location	Municip.	Lowest SRTM elevation found [m]	Lowest elevation point as shown in Croatian Base Map (geoportal.dgu.hr) [m]
Old city of Dubrovnik	Dubrovnik	8	2.6 (port in the historic town centre)
Stari Grad Field	Stari Grad	2	0.5 (waterfront in the historic town centre)
Historical Complex of Split with Palace of Diocletian	Split	2	1.7 (waterfront in front of the Palace)
Historic city of Trogir	Trogir	2	0.9 (northern part of the waterfront in historic town centre)
Cathedral of St James in Šibenik	Šibenik	1	6.5 (a square with the Cathedral)
Episcopal Complex of Euphrasian Basilica Poreč	Poreč – Parenzo	0	1.6

Figure 14: The Episcopal Complex of Euphrasian Basilica in Poreč, located at sea-level.

3.1.4 Adaptation cost

All impacts reported in Section 3.1 and 3.2 are assessed with the assumption of no adaptation measures being in place. In this section we assess the potential and cost of reducing coastal flood damage and impacts through constructing dikes. Generally, a wide range of coastal adaptation measures are available including:

(i) protection against flooding through e.g. building dikes or restoring coastal ecosystems;

(ii) accommodation measures such as flood-proofing houses and critical infrastructure; and

(iii) retreat from the coastline (Klein et al., 2001; Wong et al., 2014).

This analysis focuses on dikes because this is the most common and mature technology applied in heavily human used coastal zones. By considering dikes we do not want to suggest that this should be the sole measure applied. Which long-term strategy to take for protecting Croatia against sea-level rise is a decision that needs to be taken by all involved stakeholders. The cost estimates generated here may support this process.

In our analysis we distinguish between protecting coasts against current climate variability and future climate change. In our case, adapting to current climate variability means constructing dikes to protect against the current extreme water level regime. We thereby estimate the design height of dikes through an econometric demand-for-safety function that is in increasing in population density and GDP and is taken from Hinkel et al. (2014) as explained above. The share of Croatia's coastline considered for protection depends on the population-density threshold above which dike construction should take place. Sea dike height in 2100 under SSP2 and medium SLR scenario are presented in Figure 15.

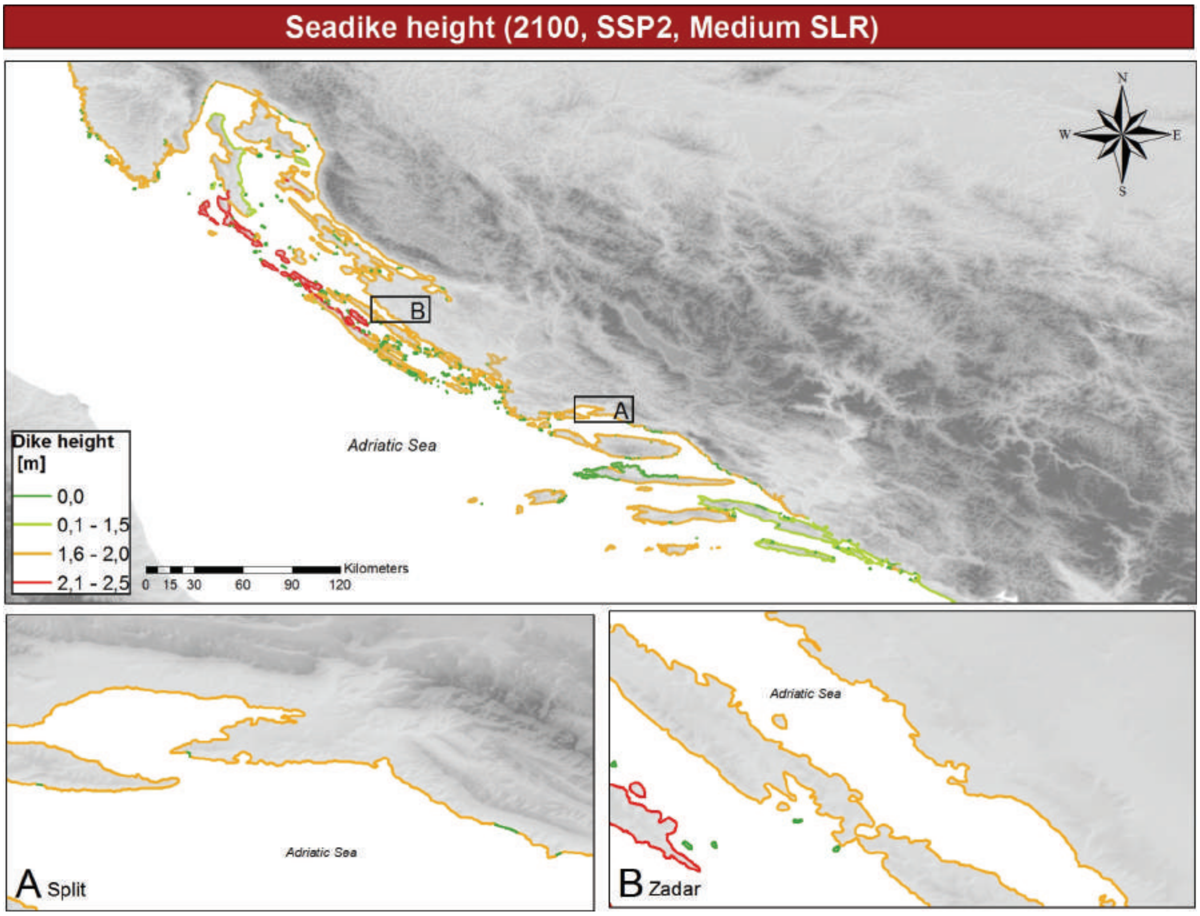

Figure 15: Sea-dike height in 2100 under SSP2 and medium SLR scenario.

If we consider protecting segments which have >30 inh./km^2 in the flood area, this would result in protecting 83.7% of coastline (4,870 km). For segments with >100 inh./km^2 it would mean protecting 67.5% of coastline (3,930 km) and for segments with >200 inh./km^2 the share would be 49.6% (2,890 km). Average dike height is around 1.2 m. More densely populated areas are protected with higher dikes. No dikes are built in coastline segments with lower population density. We must note that while we only assess dikes as an adaptation option, there are many more adaptation options available, including retreat options such as establishing set back zones.

Table 9 summarizes the initial and annual dike construction costs for today's situation and projections for 2100.

Table 9: Dike construction and maintenance cost.

	Construct. cost [million US$]	Maint. cost [million US$]	Total [million US$]	Avoided annual flood damages [million US$]
Initial cost	6,500–11,200	65–112	6,565–11,312	N/a
Annual cost, 2100	5–108	48–125	53–233	190–5,200

Initial today's costs for dike construction, which have an average design return period between 960 and 1120 years, are between 6.5 (200 inh./km^2 threshold) and 11.2 billion US$ (30 inh./km^2 threshold). These costs represent what is called adaptation deficit in the literature. Usually, these costs would be distributed over time. Assuming a planning and implementation horizon for coastal defences of 50 years (Nicholls et al., 2010a) would mean that US$ 140 million per year would need to be spent over 50 years.

Obviously, the less coast is protected by dikes, the less are the costs for this protection. However, the average dike height, as well as the average design level, remains in the same order of magnitude under all three population density thresholds.

Adapting to future climate change means upgrading existing and constructing new dikes in order to account for the increasing risks. The additional construction and the maintenance cost for this is shown in Figure 16.

While these adaptation costs are substantial, overall adaptation is cost-efficient as it reduces the impacts significantly (Figure 17; Table 9).

Locally we find the highest dikes on some of the outer islands in the north-west. This is mainly because surge heights there are higher than in other areas. A possible interpretation is that these islands are a kind of natural protection that suffers high surges, but protects the areas more inland.

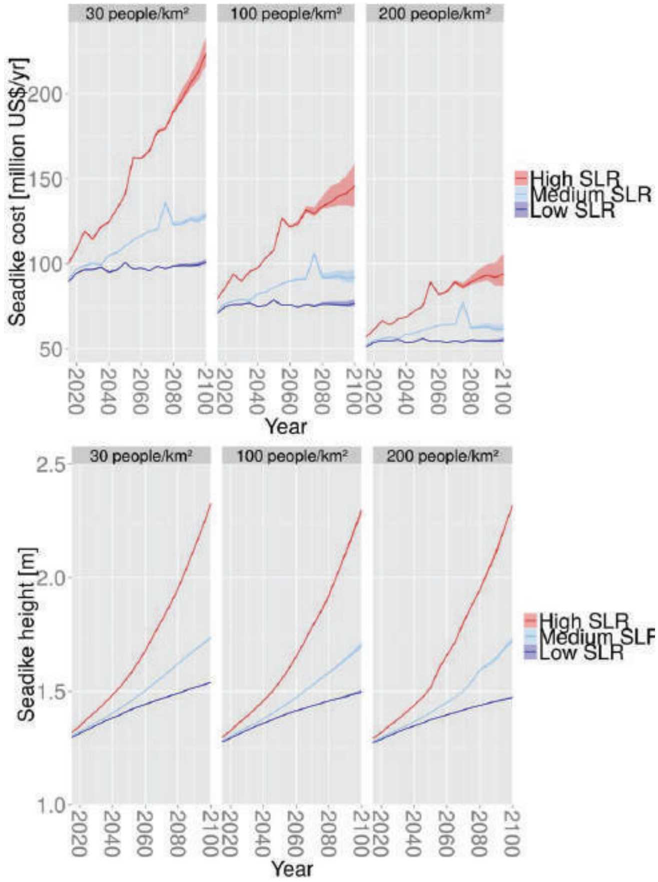

Figure 16: Annual dike construction and maintenance cost (top) and total average dike height (bottom) under different population density thresholds, sea-level rise scenarios and socio-economic scenarios (shown as shaded uncertainty range).

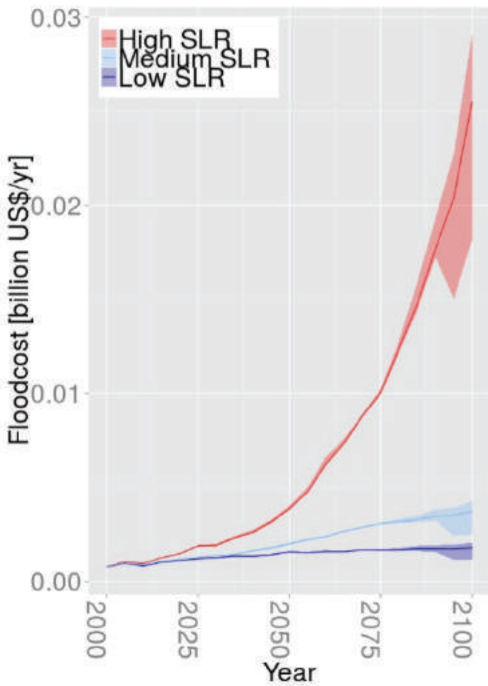

Figure 17: Expected annual coastal flood cost with adaptation.

3.2 Erosion

3.2.1 Impacts

Only a small fraction of the Croatian coastline consists of erodible beaches. In our classification we identified 189 segments that contain a fraction of erodible beach and the total length of erodible beaches in Croatia is 80.9 km. Expected annual land loss due to sea-level rise is shown in Figure 18. Without adaptation, land loss is independent from the socio-economic scenario and only the sea-level rise determines the area which is lost. Under the high sea-level rise scenario and without adaptation, sea-level rise is projected to erode 8,600 m² of land from 2010 to 2100. Under the medium sea-level rise scenario 3,800 m² are lost and under the low sea-level rise scenario 2,100 m² are lost from 2010 to 2100.

The municipalities most affected by erosion are Nin (780 m² land loss from 2010 to 2100), Dugi Rat (510 m² land loss from 2010 to 2100), Privlaka (410 m² land loss from 2010 to 2100) and Pag (410 m² land loss from 2010 to 2100).

Applying beach nourishment following the cost-benefit approach described in Section 2.4 will require up to 700 m³ of sand to be applied annually in 2100, leading to an annual cost of US$ 2.000 (Figure 19). Hence, nourishment is inexpensive, especially when compared to the value the sandy beaches add to tourism.

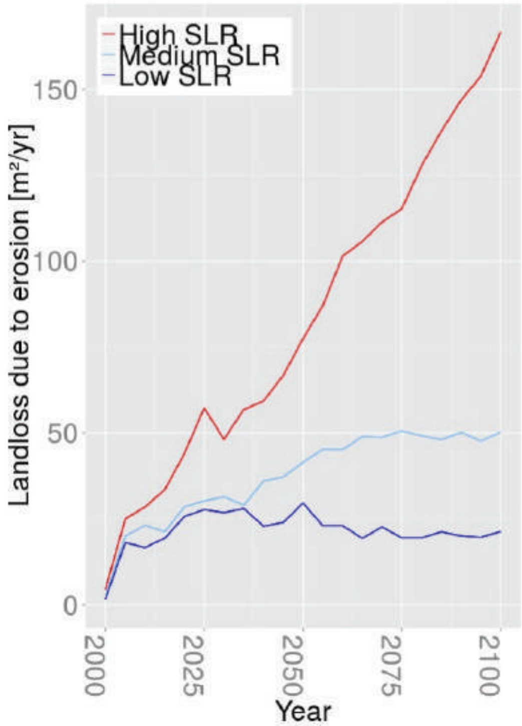

Figure 18: Annual land loss due to erosion until 2100 in Croatia under three different sea-level rise scenarios.

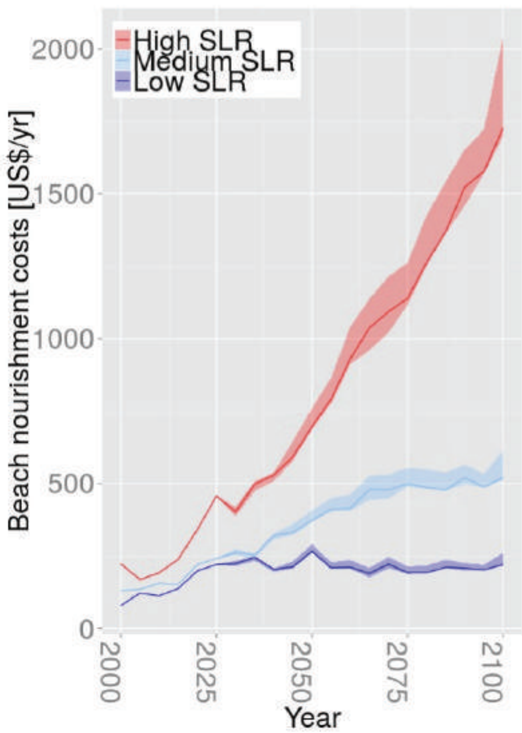

Figure 19: Annual beach-nourishment cost in Croatia under three sea-level rise scenarios until 2100.

4 Conclusions

This report presented an assessment of sea-level rise impacts on the coastal regions of Croatia using a downscaled version of the DIVA framework, an integrated model of coastal systems. The assessment was based on a full representative sample of the socio-economic and sea-level rise uncertainty space employing three sea-level rise scenarios (with a 21st century sea-level rise of 0.28 m, 0.49 m and 1.08 m) and three socio-economic development scenarios based on the shared socio-economic pathways (SSPs). The assessment considered the sea-level rise impacts of increased coastal flooding and coastal erosion. Impacts were assessed both without adaptation and with adaptation in form of upgrading dikes to protect against flooding and nourishing beaches and shores to protect against erosion.

The analysis shows that the impacts of sea-level rise will be substantial in the 21st century for Croatia if no adaptation measures are taken. Coastal flooding due to current climate variability is already an issue for Croatia. 270 km^2 of the Croatian coastal zone is currently exposed to the 1-in-100 year coastal extreme water level. 21st century sea-level rise would increase this area to 320–360 km^2. If no adaptation measures are taken, sea-level rise and socio-economic development would increase flood risks substantially during the 21st century. The expected number of people flooded annually would increase from initial 17,000 to 43,000–128,000 in 2100 and the expected annual damages from initial US$ 40 million to 0.9 to 8.9 billion per year in 2100, mainly concentrated in the floodplain areas of Zadar and Šibenik.

The analysis also shows that impacts can be reduced significantly when applying appropriate adaptation measures. Here we assessed the adaptation via dikes as one possible and widely applied strategy. This strategy would reduce sea-level rise impacts by about two orders of magnitude. The strategy assessed here would require an initial up-front investment of US$ 11.2 billion to build initial dikes for about 84% of Croatia's coast (when considering coastal segments with population density higher than 30 inh./km^2 as ones that need protection) and subsequent annual investments and maintenance costs increasing from initial about US$ 110 million per year to US$ 100–230 million at the end of the century. While these costs are substantial, they are at least one order of magnitude lower than the avoided damage costs, which means that this strategy is highly cost efficient.

We must emphasize that the proportion of the coast that requires protection (84%) is based on the assumption that entire coastal segments are to be protected if their population density exceeds 30 inh./km^2. However, coastal areas that are constructed or planned for construction (for both residence and tourism) according to today's spatial plans are only covering approximately 20%[2] of Croatia's coastline length. It is therefore important to note that the actual protection length would lie between these two values. The exact value will depend on the geographical settings (e.g. elevation, morphology, floodplain characteristics) as well as on management priorities and decisions.

It should also be highlighted that the vulnerable areas identified in this study correspond well with the patterns found in earlier studies on impacts of SLR on the Croatian coast (e.g. Barić et al., 2008). Barić et al. mention endangered coastal areas such as Neretva alluvial plane, Nin, Zadar, Split and others, which were also identified as vulnerable in this study.

Compared to the impacts of sea-level rise on coastal flooding, coastal erosion is a minor issue for Croatia. Under the high sea-level rise scenario and without adaptation, sea-level rise is projected to erode up to 8,600 m^2 of land from today to 2100. Adaptation through beach nourishment would cost up to US$ 2,000 annually. Keeping the beaches used for tourism is therefore relatively inexpensive.

[2] This calculation was performed by Baučić, M. and Berlengi, G. as an input for Marine and Coastal Strategy for Croatia.

Future work should focus on the most vulnerable regions such as Zadar and Šibenik and assess specific adaptation options for these regions. Such analytical work should also be accompanied by an exploration of how local communities can be engaged in regional responses and including a wide range of adaptation options and strategies. Finally, coastal adaptation needs to take into account the wider objectives of coastal management and development as well as the interests and conflicts amongst diverse stakeholders. For example, protecting via dikes will not be attractive for the tourism sector.

The results of this study point out the importance of restraining further urbanization along the Croatian coast. When the cost-effectiveness of flood protection measures is considered on a segment level, it is clear that these measures are cost-effective for large coastal urban areas with high density of population and assets. However, such measures are difficult to be cost-effective for long-shore urbanization which is hardly adaptable to raising sea levels, and should therefore be restrained.

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Appendix A: Estimation of Values of Housing and Tourism Facilities along Croatian Coast

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During the application of the DIVA method for the Croatian coast, the discrepancy between population projections and the intensive coastal urbanization became so obvious that it could not have been ignored. Namely, since the 1960s the population of Croatia grew by only 3%, while the urbanization of the coast was such that 4 times more was built than what all previous generations had built. National and international population projections for Croatia all indicate a decrease in population numbers. A recent national assessment shows that this drop is happening faster than any previous forecast. However, spatial plans in Croatia allow a 10-fold increase of the urbanized coast than what was there before the 1960s. The highest density of construction is, as is the case for many other Mediterranean touristic countries, in the zone closest to the sea. This zone is also the zone with the highest risks related to the sea-level rise.

Discrepancy between these two values motivated the experts involved in this project to dedicate particular attention to this issue. For that reason, a particular study has been performed, based on the actual county and city spatial plans; census data for population; houses/apartments and flats; and the tax data on real estate trading. This summary aims to present the methodology and resulting estimates of the monetary value of housing and tourist facilities, as well as buildable land of coastal Croatia.

It provides two sets of estimates: the current values at a disaggregated level across different coastal municipalities, and projected values at an aggregated level by county, i.e. average value for each of the seven coastal counties. The estimates were based on the market values given by the Croatian tax office, Ministry of Finance. These values were supplied for 127 coastal municipalities and towns (in Kuna/m^2) for the following categories: buildable land, apartments, individual houses and offices. For the remaining 7 municipalities that belong to the coastal zone[3] PAP/RAC provided an estimation. The market values for the last three categories were given in relation to the age and size of the asset, for all transactions that occurred within one month (August or September 2013). These values were then aggregated to give an average value for "developed/mixed" land, while the first category was reported separately as "buildable land". The current values are available for each municipality, as well as for polygons (x km by x km) within each municipality in the database that contains 37,925 polygons of land.

The calculations of values that were applied to each polygon of every municipality were made as follows:

- For "developed/mixed" land, first the total value of the developed/mixed assets for each municipality was calculated. This was done by multiplying the average price of m^2 of municipality flats, houses, offices and businesses (from tax data) by the total number of m^2 of flats in the municipality. This total value of developed/mixed assets in the municipality was then divided by the total number of m^2 of developed mixed land in the municipality, in order to obtain the average value of each m^2 of developed mixed land in the municipality [Kuna/m^2].
- For "buildable land" the average price of m^2 of buildable land in the municipality was directly estimated from the tax data. Therefore, the total value of buildable land in the municipality was

[3] During the preparation of the Law on Ratification of the ICZM Protocol for the Mediterranean, and later on in the Decision on the preparation of the National Marine and Coastal Strategy, the Government of Croatia defined the geographical coverage of the coastal zone as the territorial sea from the marine side, and 134 coastal municipalities and towns whose territory encompasses the 1,000 m of the protected coastal zone from the land side. No data were provided for the municipalities of Dubrovačko primorje, Janjina, Milna, Ston, Zadvarje, Župa Dubrovačka and Funtana.

calculated by multiplying these average prices per m^2 by the total number of m^2 of buildable land in the municipality.

The total values derived for different municipalities range from a low US$ 65.8 million[4] in Zadvarje to a high US$ 8,600 million in Rijeka. The average value of a municipality in coastal Croatia is around US$ 900.5 million. At the county level, the data for 2015 show that the highest total values are in the Split-Dalmatia county (US$ 29 billion), while the lowest are in the Lika-Senj county (US$ 2 billion).

For future values the report has used three socio-economic scenarios: Shared Socio-economic Pathways (SSP1, SSP2 and SSP5), developed by the climate change research community. Each of the SSPs defines projections of GDP and population for Croatia. GDP projections were adjusted for early years based on the estimates by the team of local experts. The SSP1 assumes comparatively good progress towards sustainability within an open globalized economy and, as a result, Croatia has an average *per capita* annual income growth rate of about 1.3% up to the year 2050 (starting from the present negative values). The SSP2 envisages less progress towards sustainability and a lower growth rate – around 1.2% *per annum*. Finally the SSP5 assumes a high conventional development pathway with a growth in *per capita* GDP of 1.6% *per annum*.

In addition, the calculation of future values of assets requires assumptions on:

(a) how fast the buildable land is built upon; and

(b) what is the density of new buildings.

Regarding (a) the assumption for all three scenarios is that all buildable land will be converted to developed land by 2050 at the latest. In Scenario 1 this takes place at a constant rate over the period 2015–2050. In Scenario 2 the rate of conversion is faster so that by 2035 all buildable land is converted. Finally, in Scenario 5 the assumption is that of even more rapid development, and the conversion from buildable to developed land is assumed to be completed by 2025.

Regarding (b), as far as the density of new construction (in built square meters per hectare of land) is concerned, we assume that the current densities will increase according to what is allowed by the spatial plans of today. This increase will take place gradually, so that by 2050 the weighted average density in the seven coastal counties will be 243 inh./km^2. The resulting density is close to that of coastal regions of France today (285 inh./km^2), despite the fact that the present-day density of coastal population in Croatia is less than one third of that in France. Moreover, all population projections for Croatia show decrease in population, and the current data confirm these projections, even intensifying the projected decline. This increase in density can be therefore attributed to:

(a) migration from the inland regions of Croatia to the coastal ones; and

(b) construction of secondary homes for Croatians and foreigners.

The data show that the total housing and tourism facility values are estimated at around US$ 110 billion in 2015, rising to between US$ 237 billion and US$ 262 billion by 2050, depending on the scenario. This represents a growth rate of between 2.2 and 2.5% *per annum*. This comparatively modest increase in values reflects similar modest expectations of the GDP growth for the country over this period. At the same time, these values are significant when compared to the country's output. In 2013, for example, Croatia had a GDP of around US$ 57 billion, making the coastal assets worth about two times that figure.

[4] All values expressed in US dollars are based on Kuna-to-dollar exchange rate of 20 February 2015, Croatian National Bank.

Appendix B: Detailed Results for Floodplain Areas

B1 Potential flood area

Table B1.1: Potentially flooded area (below H100) per floodplain area in 2050 and 2100 under different SLR scenarios compared with today's situation.

Floodplain area	Potential flood area (km²)						
	Today	2050			2100		
		Low SLR	Medium SLR	High SLR	Low SLR	Medium SLR	High SLR
Neretva Delta	81.3	89.0	91.6	100.2	98.0	103.8	106.1
Zadar	11.2	12.1	12.3	12.9	12.8	13.5	15.5
Murter – Kornati	9.8	10.7	11.0	11.6	11.4	12.1	13.7
Pag	9.3	10.1	10.4	10.9	10.9	11.2	13.2
Mali Lošinj	9.3	9.8	9.9	10.5	10.4	11.3	12.2
Šibenik	8.7	9.6	9.9	10.8	10.6	11.5	13.2
Tar – Vabriga	7.3	8.1	8.3	9.1	8.9	9.5	10.3
Sali	6.1	6.6	6.7	6.9	6.9	7.2	8.1
Kaštela Bay	5.4	5.9	6.1	6.6	6.5	7.1	8.1
Umag	4.9	5.4	5.5	6.0	5.9	6.4	7.2

Table B1.2: Potentially flooded area (below H100) per built-up clusters within the four major cities in 2050 and 2100 under different SLR scenarios compared with today's situation.

Built-up cluster[5]	Potential flood area (km²)						
	Today	2050			2100		
		Low SLR	Medium SLR	High SLR	Low SLR	Medium SLR	High SLR
Pula	2.05	2.24	2.31	2.52	2.46	2.73	3.32
Zadar	1.71	1.87	1.92	2.1	2.06	2.25	2.61
Split	1.52	1.66	1.71	1.9	1.83	1.97	2.18
Rijeka	0.28	0.31	0.32	0.35	0.34	0.40	0.60

B2 Assets and Population in the floodplain

Table B2.1: Assets in the floodplain in 2050 under different SLR scenarios compared and SSPs compared with today's situation.

Floodplain area	Assets Below H100 (Million US$) in 2050									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Zadar	210	530	490	640	570	530	700	710	650	860
Šibenik	180	490	450	590	530	490	650	670	620	820
Kaštela Bay	170	460	420	560	500	460	610	640	590	780
Vodice	120	320	300	390	350	320	430	450	410	540
Novalja	120	310	280	380	330	300	400	380	350	460
Neretva Delta	110	290	270	360	320	290	390	410	370	500
Vir	110	270	250	330	290	270	360	350	330	430
Umag	74	200	180	240	210	200	260	270	250	330
Privlaka	63	170	150	200	180	170	220	230	210	280
Sukošan	55	145	130	175	160	145	190	200	185	245

[5] The extent of built-up cluster is estimated based on satellite imagery.

Table B2.2: Assets in the floodplain in built-up clusters within the four major coastal cities in Croatia in 2050 under different SLR scenarios and SSPs compared with today's situation.

Built-up cluster	Assets Below H100 (Million US$) in 2050									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Zadar	150	390	360	470	420	390	520	540	490	660
Pula	34	88	81	110	96	88	120	120	110	150
Split	28	72	67	88	79	73	97	100	92	120
Rijeka	4.3	11	10	13	12	11	15	15	14	19

Table B2.3: Assets in the floodplain in 2100 under different SLR scenarios compared and SSPs compared with today's situation.

Floodplain area	Assets Below H100 (Million US$) in 2100									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Zadar	210	990	1,000	1,500	1,200	1,200	1,800	1,500	1,500	2,200
Šibenik	180	940	960	1,400	1,100	1,100	1,700	1,300	1,300	1,900
Kaštela Bay	170	890	900	1,300	1,100	1,100	1,700	1,500	1,500	2,200
Vodice	120	620	640	920	730	750	1,100	830	850	1,300
Novalja	120	560	570	840	600	610	910	730	750	1,100
Neretva Delta	110	570	580	860	660	670	990	690	710	1,000
Vir	110	510	520	760	570	590	870	700	710	1,100
Umag	74	380	390	570	470	480	710	620	630	930
Privlaka	63	320	330	490	380	390	580	450	450	670
Sukošan	55	280	280	420	330	340	500	380	390	580

Table B2.4: Assets in the floodplain in built-up clusters within the four major coastal cities in Croatia in 2100 under different SLR scenarios and SSPs compared with today's situation.

Built-up cluster	Assets Below H100 (Million US$) in 2100									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Zadar	150	750	770	1,100	900	920	1,400	1,100	1,100	1,700
Pula	34	170	170	260	210	220	320	300	300	450
Split	28	140	140	210	170	180	260	240	240	360
Rijeka	4.3	21	21	32	40	40	60	110	120	170

Table B2.5: People in the floodplain in 2050 under different SLR scenarios and SSPs compared with today's situation.

Floodplain area	Population Below H100 in 2050									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Kaštela Bay	10,600	14,100	14,000	14,200	15,300	15,400	15,400	19,500	19,400	19,600
Neretva Delta	4,200	5,600	5,600	5,600	6,100	6,100	6,100	7,700	7,700	7,800
Rijeka	3,600	4,600	4,600	4,700	5,000	5,000	5,100	6,400	6,400	6,500
Zadar	3,500	4,500	4,400	4,500	4,800	4,800	4,900	6,100	6,000	6,100
Šibenik	2,200	2,900	2,900	2,900	3,200	3,100	3,200	4,000	4,000	4,000
Pula	2,000	2,600	2,600	2,600	2,800	2,800	2,800	3,600	3,500	3,600
Umag	1,700	2,200	2,200	2,200	2,400	2,400	2,400	3,100	3,100	3,100
Dubrovnik	1,400	1,800	1,800	1,800	2,000	2,000	2,000	2,500	2,500	2,500
Mali Lošinj	1,300	1,300	1,200	1,300	1,300	1,300	1,300	1,300	1,300	1,300
Crikvenica	1,200	1,500	1,500	1,500	1,600	1,600	1,600	2,100	2,100	2,100

Table B2.6: People in the floodplain in built-up clusters within the four major coastal cities in Croatia in 2050 under different SLR scenarios and SSPs compared with today's situation.

Built-up cluster	Population Below H100 in 2050									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Split	3,500	4,600	4,600	4,700	5,000	5,000	5,100	6,400	6,400	6,400
Rijeka	3,500	4,600	4,600	4,700	5,000	5,000	5,100	6,400	6,400	6,400
Zadar	2,700	3,600	3,600	3,600	3,900	3,900	3,900	5,000	5,000	5,000
Pula	1,900	2,600	2,600	2,600	2,800	2,800	2,800	3,600	3,500	3,600

Table B2.7: People in the floodplain in 2100 under different SLR scenarios and SSPs compared with today's situation.

Floodplain area	Population Below H100 in 2100									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Kaštela Bay	10,600	14,600	18,000	12,100	16,800	21,000	13,900	17,300	21,300	14,300
Neretva Delta	4,200	5,600	5,600	5,600	6,100	6,100	6,100	7,800	7,700	7,800
Rijeka	3,600	4,800	5,900	4,000	5,600	6,900	4,600	5,900	7,200	4,900
Zadar	3,500	4,500	5,600	3,700	5,200	6,400	4,300	5,500	6,700	4,500
Šibenik	2,200	3,000	3,700	2,500	3,400	4,200	2,800	3,500	4,300	2,900
Pula	2,000	2,700	3,300	2,200	3,200	3,800	2,500	3,200	4,000	2,700
Umag	1,700	2,300	2,800	1,900	2,700	3,300	2,200	2,700	3,400	2,300
Dubrovnik	1,400	1,900	2,300	1,600	2,600	3,200	2,200	3,500	4,300	2,900
Mali Lošinj	1,300	1,000	1,200	830	1,000	1,300	900	1,100	1,300	900
Crikvenica	1,200	1,600	2,900	1,300	1,800	2,200	1,500	1,800	2,200	1,500

Table B2.8: People in the floodplain in built-up clusters within the four major coastal cities in Croatia in 2100 under different SLR scenarios and SSPs compared with today's situation.

Built-up cluster	Population Below H100 in 2100									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Split	3,500	4,800	5,900	4,000	5,600	6,900	4,600	5,900	7,200	4,900
Rijeka	3,500	4,800	5,900	4,000	5,600	6,800	4,600	5,800	7,100	4,800
Zadar	2,700	3,700	4,600	3,100	4,300	5,300	3,600	4,400	5,400	3,700
Pula	1,900	2,700	3,300	2,200	3,100	3,800	2,600	3,200	4,000	2,700

B3 People flooded annually

Table B3.1: Expected number of people flooded annually per floodplain area in 2050 under different SLR scenarios and SSPs compared with today's situation.

Floodplain area	People flooded annually in 2050									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Kaštela Bay	2,900	6,900	6,900	7,000	8,200	8,100	8,200	12,300	12,300	12,400
Neretva Delta	1,100	2,700	2,700	2,800	3,300	3,200	3,200	4,900	4,900	4,900
Rijeka	1,100	2,300	2,200	2,300	2,700	2,600	2,700	4,100	4,000	4,100
Zadar	1,000	2,200	2,100	2,200	2,500	2,500	2,600	3,800	3,800	3,900
Šibenik	630	1,400	1,400	1,400	1,700	1,700	1,700	2,500	2,500	2,600
Pula	560	1,300	1,300	1,300	1,500	1,500	1,500	2,300	2,200	2,300
Umag	480	1,100	1,100	1,100	1,300	1,300	1,300	1,900	1,900	2,000
Dubrovnik	400	900	900	900	1,100	1,100	1,100	1,600	1,600	1,600
Mali Lošinj	340	580	580	590	670	660	670	930	920	930
Crikvenica	330	730	730	740	970	860	870	1,300	1,300	1,300

Table B3.2: Expected number of people flooded annually in built-up clusters within the four major coastal cities in 2050 under different SLR scenarios and SSPs compared with today's situation.

Built-up cluster	People flooded in 2050									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Split	1,100	2,300	2,300	2,300	2,700	2,700	2,700	4,100	4,000	4,100
Rijeka	1,100	2,300	2,300	2,300	2,700	2,700	2,700	4,100	4,000	4,100
Zadar	860	1,800	1,800	1,800	2,100	2,100	2,100	3,200	3,100	3,200
Pula	610	1,300	1,300	1,300	1,500	1,500	1,500	2,300	2,200	2,300

Table B3.3: Expected number of people flooded annually per floodplain area in 2100 under different SLR scenarios and SSPs compared with today's situation.

Floodplain area	People flooded annually in 2100									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Kaštela Bay	2,900	8,900	11,000	7,400	14,300	17,600	11,800	17,200	21,100	14,200
Neretva Delta	1,100	3,600	4,400	2,900	5,700	7,000	4,700	6,700	8,300	5,600
Rijeka	1,100	2,900	3,600	2,400	4,700	5,800	3,900	5,800	7,100	4,800
Zadar	1,000	2,800	3,400	2,300	4,400	5,400	3,600	5,300	6,600	4,400
Šibenik	630	1,800	2,300	1,500	2,900	3,600	2,400	3,400	4,300	2,900
Pula	560	1,600	2,000	1,300	2,600	3,200	2,200	3,200	3,900	2,600
Umag	480	1,400	1,700	1,200	2,300	2,800	1,900	2,700	3,300	2,200
Dubrovnik	400	1,200	1,400	970	1,900	2,300	1,600	3,500	4,300	2,900
Mali Lošinj	340	680	840	560	960	1,200	900	1,000	1,300	850
Crikvenica	330	940	1,200	780	1,200	1,800	1,300	1,800	2,200	1,500

Table B3.4: Expected number of people flooded annually per built-up cluster within four major coastal cities in 2100 under different SLR scenarios and SSPs compared with today's situation.

Built-up cluster	People flooded in 2100									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Split	1,100	2,900	3,600	2,400	4,700	5,800	3,900	5,700	7,000	4,700
Rijeka	1,100	2,900	3,600	2,400	4,600	5,800	3,900	5,700	7,100	4,700
Zadar	860	2,300	2,800	1,900	3,700	4,500	3,000	4,400	5,400	3,600
Pula	610	1,600	2,000	1,300	2,600	3,200	2,200	3,200	3,900	2,600

B4 Sea-flood damages

Table B4.1: Expected damages caused by sea-floods under different SLR scenarios compared and SSPs compared with today's situation.

Floodplain area	Sea-flood cost (Million US$) in 2050									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
Zadar	3.6	25	23	31	33	31	41	68	63	83
Šibenik	2.9	23	21	28	31	28	37	64	59	78
Kaštela Bay	2,5	22	20	26	29	27	36	60	56	74
Novalja	2.2	14	13	17	19	17	23	37	34	46
Vodice	1.9	15	14	19	20	19	25	42	39	52
Vir	1.8	13	12	15	17	15	20	34	32	42
Neretva Delta	1,6	14	13	17	18	17	23	39	36	47
Umag	1.2	9.2	8.5	11	12	11	15	26	24	32
Privlaka	1.0	7.8	7.2	9.6	11	9.7	13	22	20	27
Sukošan	0.9	6.8	6.2	8.3	9.1	8.5	11	19	17	23

Table B4.2: Expected damages caused by sea-floods in built-up clusters within the four major coastal cities in Croatia under different SLR scenarios compared and SSPs compared with today's situation.

Built-up cluster	Sea-flood cost (Million US$) in 2050									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	*SSP3*	*SSP5*	*SSP2*	*SSP3*	*SSP5*	*SSP2*	*SSP3*	*SSP5*
Zadar	2.6	18	17	22	24	30	23	51	47	62
Pula	0.6	4.1	3.8	5.0	5.6	5.1	6.8	12	11	14
Split	0.5	3.4	3.1	4.1	4.6	4.2	5.6	9.5	8.8	12
Rijeka	0.1	0.5	0.5	0.6	0.7	0.6	0.8	1.5	1.3	1.8

Table B4.3: Expected damages caused by sea-floods in 2100 under different SLR scenarios compared and SSPs compared with today's situation.

Floodplain area	Sea-flood cost (Million US$) in 2100									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	*SSP3*	*SSP5*	*SSP2*	*SSP3*	*SSP5*	*SSP2*	*SSP3*	*SSP5*
Zadar	3.6	86	88	130	200	200	300	540	560	820
Šibenik	2.9	80	82	120	190	190	280	510	520	770
Kaštela Bay	2,5	76	78	115	180	180	270	520	530	790
Novalja	2.2	47	48	66	110	110	160	280	280	420
Vodice	1.9	53	54	71	120	130	155	340	340	420
Vir	1.8	43	44	65	99	100	150	270	270	400
Neretva Delta	1,6	48	50	73	113	115	170	300	300	450
Umag	1.2	33	33	49	76	78	110	220	220	330
Privlaka	1.0	28	28	42	64	66	97	180	190	260
Sukošan	0.9	24	24	36	56	57	84	150	150	230

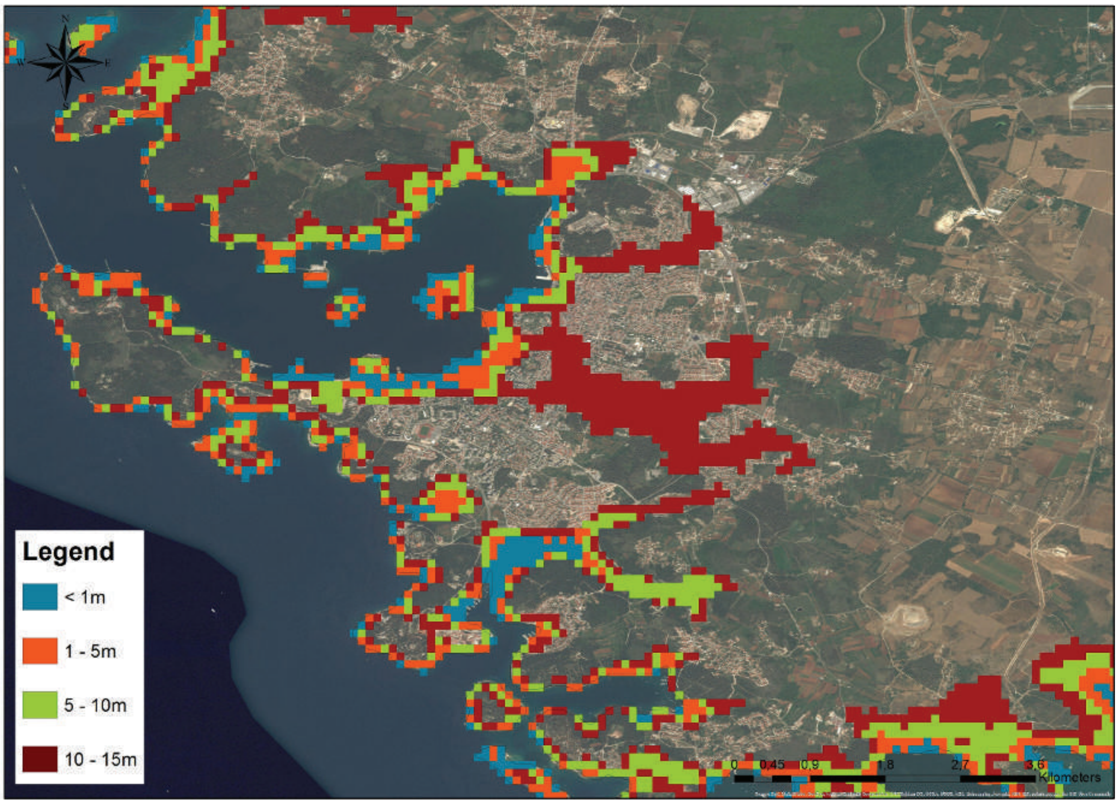
Table B4.4: Expected damages caused by sea-floods in 2100 in built-up clusters within the four major coastal cities in Croatia under different SLR scenarios and SSPs compared with today's situation.

Built-up cluster	Sea-flood cost (Million US$) in 2100									
	Today	Low SLR			Medium SLR			High SLR		
		SSP2	*SSP3*	*SSP5*	*SSP2*	*SSP3*	*SSP5*	*SSP2*	*SSP3*	*SSP5*
Zadar	2.6	64	65	97	150	150	230	420	430	630
Pula	0.6	15	15	22	34	35	51	100	100	150
Split	0.5	12	12	18	28	29	42	82	84	120
Rijeka	0.1	1,9	1,9	2,8	4,3	4,4	6,5	23	24	35

Appendix C:
Inundation Maps

C1 Pula

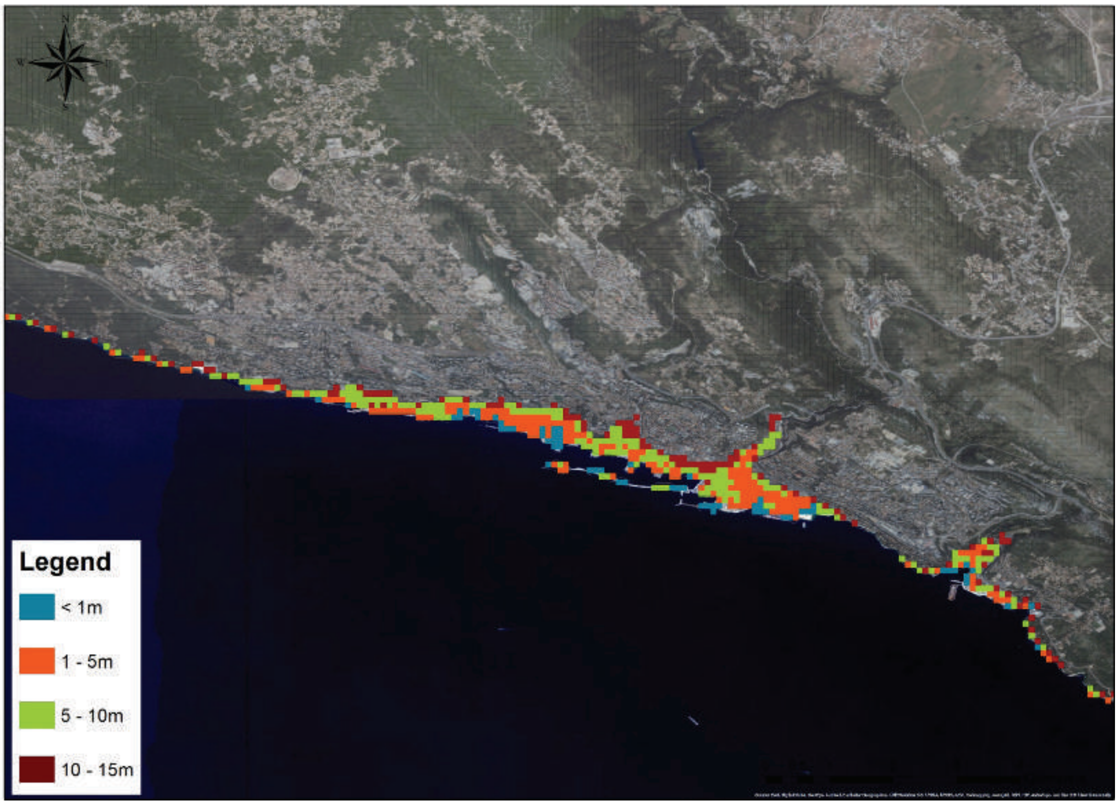
Inundation areas - Pula



Inundation areas below 15m - Pula

C2 Rijeka

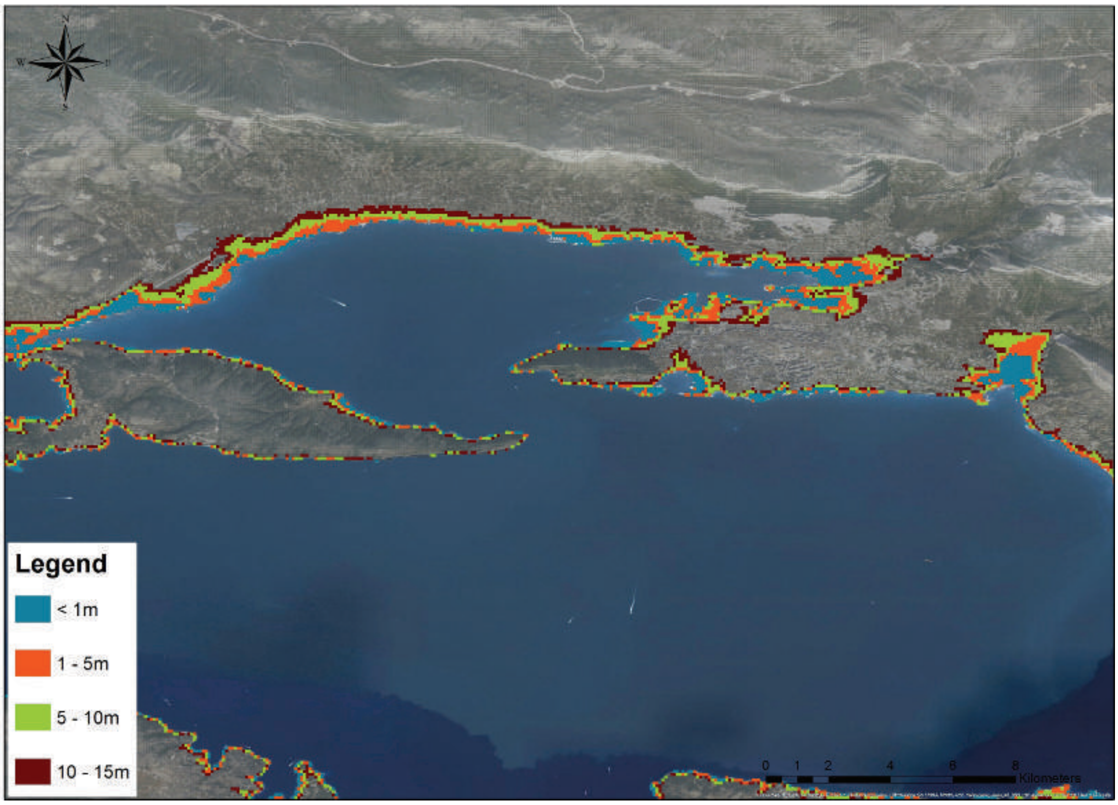
Inundation areas - Rijeka



Inundation areas below 15m - Rijeka

C3 Split

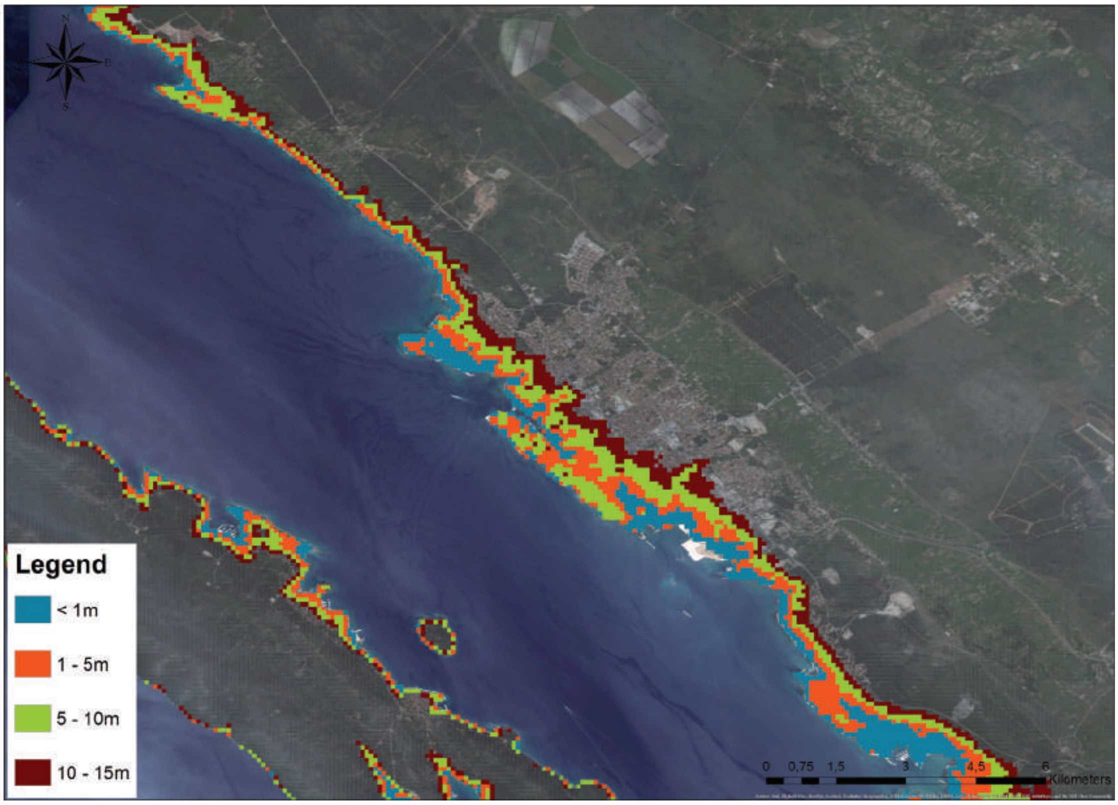
Inundation areas - Split



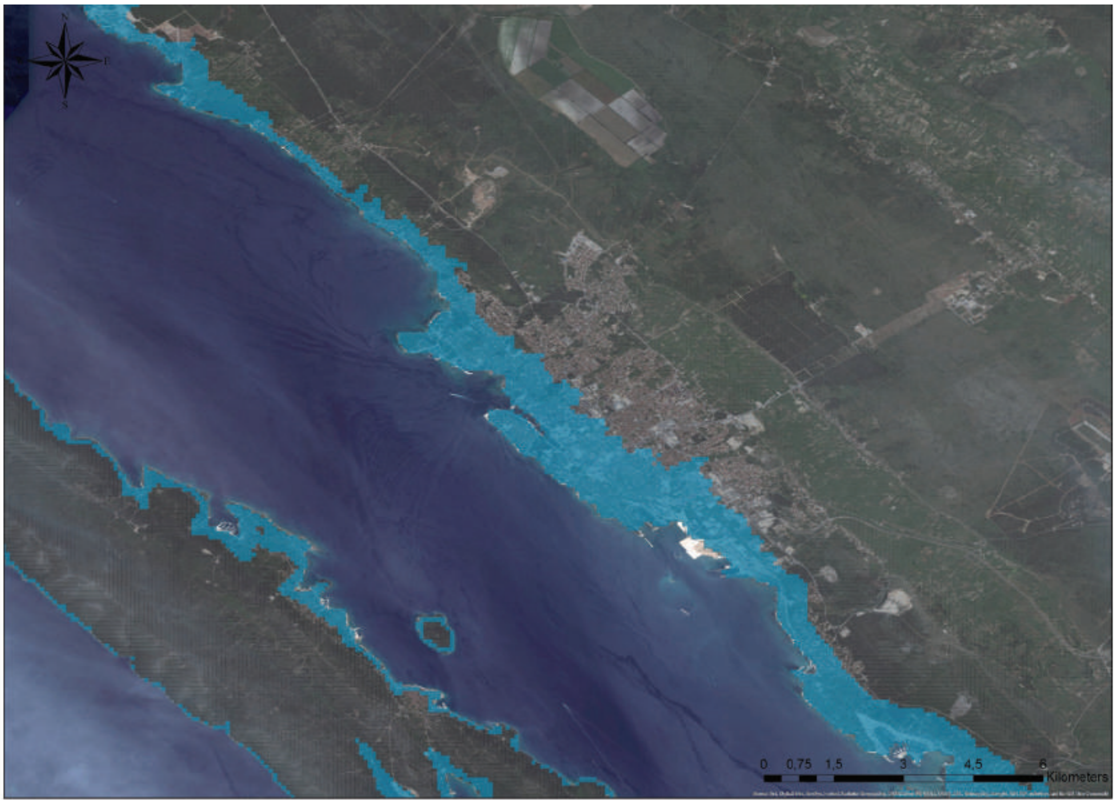
Inundation areas below 15m - Split

C4 Zadar

Inundation areas - Zadar



Innundation areas below 15m - Zadar



Strategic Partnership for the Mediterranean Sea Large Marine Ecosystem

MedPartnership

Together for the Mediterranean Sea

GEF

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MINISTRY OF ENVIRONMENT
AND NATURE PROTECTION

PAP/RAC

Strategic Partnership for the Mediterranean Sea Large Marine Ecosystem

MedPartnership

Together for the Mediterranean Sea

GEF UNEP

PAP/RAC

PAP/RAC is established in 1977 in Split, Croatia, as a part of the Mediterranean Action Plan (MAP) of the United Nations Environment Programme (UNEP). PAP/RAC's mandate is to provide support to Mediterranean countries in the implementation of the Barcelona Convention and its Protocols, and in particular of the Protocol on Integrated Coastal Zone Management. PAP/RAC is oriented towards carrying out of the activities contributing to sustainable development of coastal zones and strengthening capacities for their implementation. Thereby, it co-operates with the national, regional and local authorities, as well as with a large number of international organisations and institutions.