Project: “Monitoring Sea-water intrusion in coastal aquifers and Testing pilot projects for its mitigation” Interreg CBC Italy-Croatia 2014.-2020.

Priority Axis: Safety and resilience

Specific objective: Improve the climate change monitoring and planning of adaptation measures tackling specific effects, in the cooperation area

(D_5.1.1) Vulnerability map, including expected scenarios of climate changes (in Croatian)

Work Package 5: Transferring

Activity 1: Neretva plan of adaptation

Partner in charge: PP4 (UNIST-FGAG)

Partners involved: PP4 (UNIST-FGAG), PP5 (CROATIAN WATERS), PP6 (DUNEA)

Final version

Public report

September, 2022

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Climate changes

The aim of this report is to define main variables for climate change projections. Defined variables will be used in numerical model of river Neretva as an activity proposed by the project: “Monitoring Sea-water intrusion in coastal aquifers and Testing pilot projects for its mitigation” Interreg CBC Italy-Croatia 2014.-2020.

This report will present projections of climate change for temperature, precipitation and sea level rise from multiple sources. Global, European and Croatian projections for climate changes will be shown. The most relevant sources of information for climate change projections are IPCC (The Intergovernmental Panel on Climate Change) and EEA (The European Environment Agency).

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. The IPCC was created to provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options. [1]

The European Environment Agency (EEA) provides sound, independent information on the environment for those involved in developing, adopting, implementing and evaluating environmental policy, and also the general public. In close collaboration with the European Environmental Information and Observation Network (Eionet) and its 32 member countries, the EEA gathers data and produces assessments on a wide range of topics related to the environment. [2]

IPCC and EEA are explaining climate change projections trough Representative Concentration Pathways (RCPs) and Socioeconomic Pathways (SSPs).

Representative Concentration Pathways (RCPs) have been introduced to climate change research for classifying the stringency of different warming limits. RCPs constitute projections of greenhouse gas emissions and concentrations and their combined radiative forcing. They originally comprised four projections, ranging from RCP 2.6 to RCP 8.5, and after the adoption of the Paris Agreement were augmented by RCP 1.9 to represent mitigation pathways compatible with the 1.5 °C warming limit. The values refer to radiative forcing in Watt/m2 by the end of the century compared to preindustrial times. [3]

Table 1 Representative Concentration Pathways (RCP) [3]

RCP	Forcing	Temperature	Emission Trend
1.9	1.9 W/m2	~1.5 °C	Very Strongly Declining Emissions
2.6	2.6 W/m2	~2.0 °C	Strongly Declining Emissions
4.5	4.5 W/m2	~2.4 °C	Slowly Declining Emissions
6.0	6.0 W/m2	~2.8 °C	Stabilising Emissions
8.5	8.5 W/m2	~4.3 °C	Rising Emissions

The Shared Socioeconomic Pathways (SSPs) are part of a new framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation and mitigation.

The database includes projections for population (by age, sex, education and urbanization) and economic development (GDP).

In addition to the basic SSP socio-economic elements, the database includes preliminary SSP-based scenarios by integrated assessment models (IAMs). The scenarios provide detailed global and regional projections, among others, for energy supply and use, land-use, GHG and air pollutant emissions, average global radiative forcing and temperature change and mitigation costs. [4]

Projected changes in ground air temperature

Based on EEA, global annual near surface temperature has been rising steadily since the end of the 19th century. The rate of increase has been particularly high since the 1970s at about 0.2°C per decade. In this period, global temperature has risen faster than in any other 50-year period over at least 2000 years, with the past six years (2015–2020) being the warmest on record.

Climate modelling has been used to estimate future climate change for different emissions scenarios and socio-economic pathways underlying these scenarios (Shared Socioeconomic Pathways, SSP). Without significant efforts to curtail emissions, the increase in global temperature will continue rapidly and even accelerate.

Global temperatures are projected to increase by 2.1-3.5°C above pre-industrial levels under SSP2-4.5 and by 3.3-5.7°C under SSP5-8.5 by the end of the 21st century. The only scenarios with a chance to stay within the limits established by the Paris Agreements are SSP1-1.9 with projected warming of 1.0–1.8°C and SSP1-2.6 with ranges between 1.3 to 2.4°C till the end of the 21st century compared to pre-industrial levels. These scenarios assume a drastic reduction in emissions in the coming decades and the decline of CO2 emissions to zero and subsequently negative net emissions around the year 2050 (scenario SSP1-1.9) or around 2080 (scenario SSP1-2.6). [5]

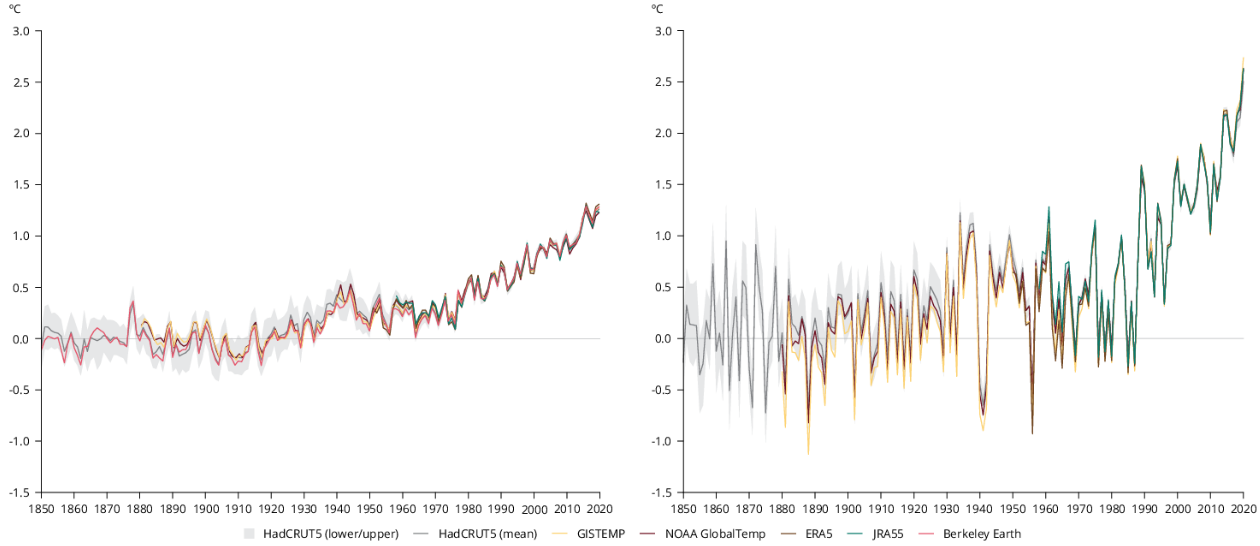


Figure 1 Global (left) and European land (right) average near-surface temperatures anomalies relative to the pre-industrial period [5]

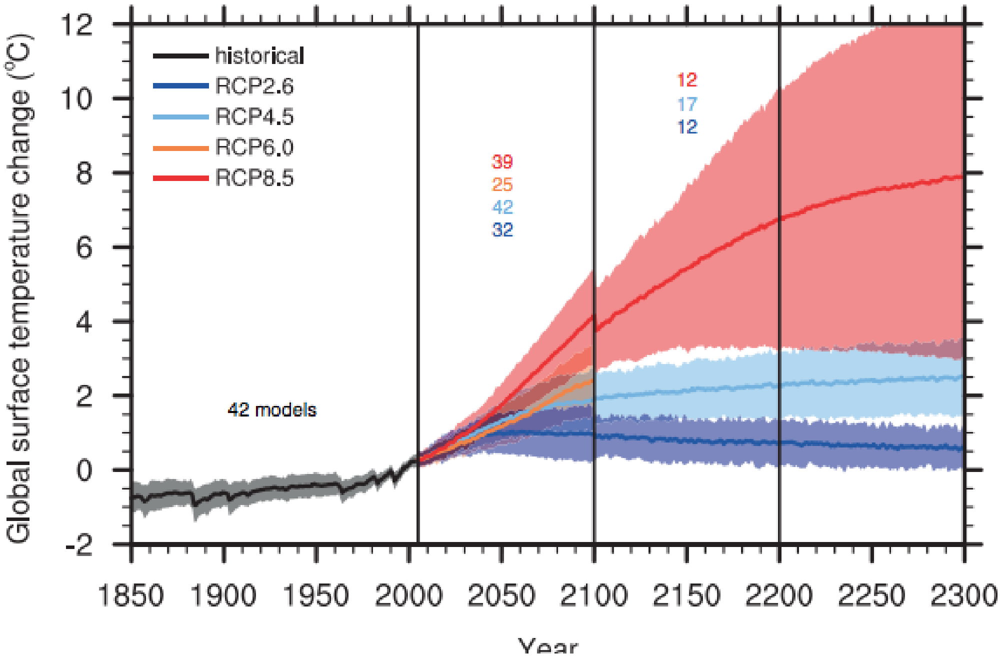


Figure 2 Extended Model Projections of Future Warming Under various IPCC Emissions Scenarios [6]

Europe is warming faster than the global average. The mean annual temperature over European land areas in the last decade was 1.94 to 2.01°C warmer than during the pre-industrial period. The year 2020 was the warmest year in Europe since the instrumental records began according to all datasets used, with the range of anomaly between 2.51°C and 2.74°C above the pre-industrial levels. Particularly high warming has been observed over eastern Europe, Scandinavia and at eastern part of Iberian Peninsula.

Projections from the CMIP6 initiative suggest that temperatures across European land areas will continue to increase throughout this century at a higher rate than the global average. Land temperatures in Europe are projected to increase further by 1.2 to 3.4° under the SSP1-2.6 scenario and by 4.1 to 8.5°C under the SSP5-8.5 scenario (by 2071-2100, compared to 1981–2010). The highest level of warming is projected across north-eastern Europe, northern Scandinavia and inland areas of Mediterranean countries, while the lowest warming is expected in western Europe, especially in the United Kingdom, Ireland, western France, Benelux countries and Denmark. [5]

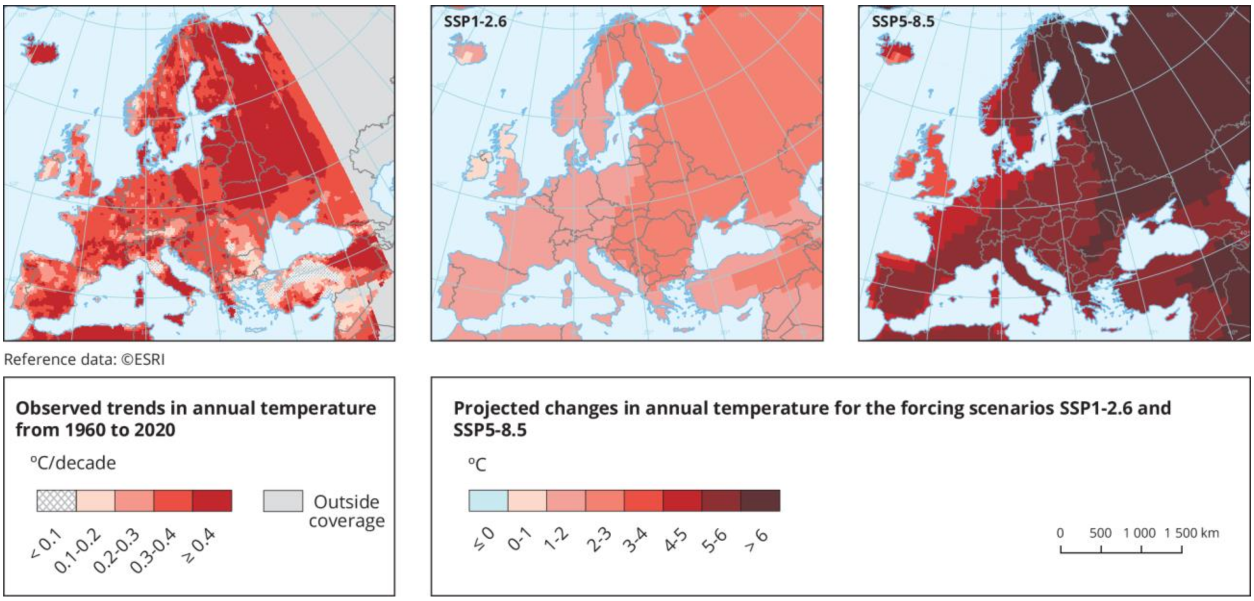


Figure 3 Observed annual mean temperature trend from 1960 to 2020 (left panel) and projected 21st century temperature change under different SSP scenarios (right panels) in Europe [5]

The State Hydrometeorological Institute (DHMZ) uses the regional climate model RegCM [7] from the International Center for Theoretical Physics in Trieste, Italy. For current climate change simulations, the model takes the initial and boundary conditions from combined global climate model ECHAM5 / MPI-OM [8].

Dynamic adaptation to the RegCM regional model was made for all three implementations of the ECHAM5 / MPI-OM model for two separate periods of current and future climate (time-slice experiment). The current climate is presented in the period 1961-1990, while the future climate according to the A2 scenario is defined in the period 2011-2070. The domain of the regional model covers most of Europe and the Mediterranean area with a spatial step of 35 km. [9]

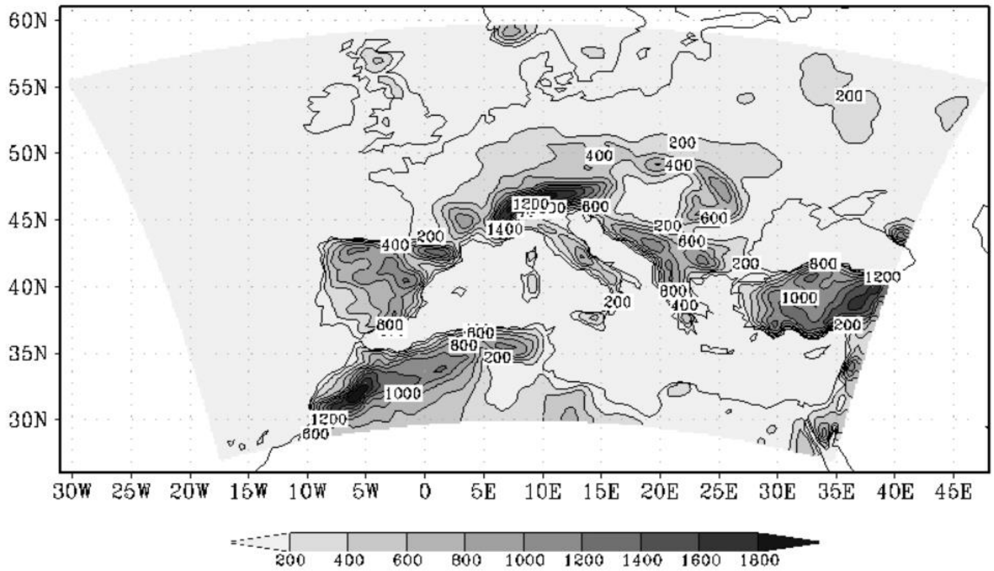


Figure 4 Domain of RegCM model with relief (m) [9]

Future climate changes in Croatia obtained by climate simulations on the regional climate model RegCM according to the A2 scenario were analysed for two 30-year periods:

1. The period from 2011 to 2040 represents the near future and is of the greatest interest to users of climate information in long-term planning of adaptation to climate change.
2. The period from 2041 to 2070 represents the middle of the 21st century, in which, according to the A2 scenario, a further increase in the concentration of carbon dioxide (CO2) in the atmosphere is predicted and the signal of climate change is stronger.

According to the results of RegCM for Croatian area, the average of the simulation ensemble indicates an increase in air temperature in both periods and in all seasons. The amplitude of the increase is higher in the second than in the first period, but is statistically significant in both periods. The increase in the average daily air temperature is higher in summer (June - August) than in winter (December - February). [9]

In the first period of the future climate (2011-2040), the temperature in Croatia is expected to rise to 0.6 ° C in winter and to 1 ° C in summer [10].

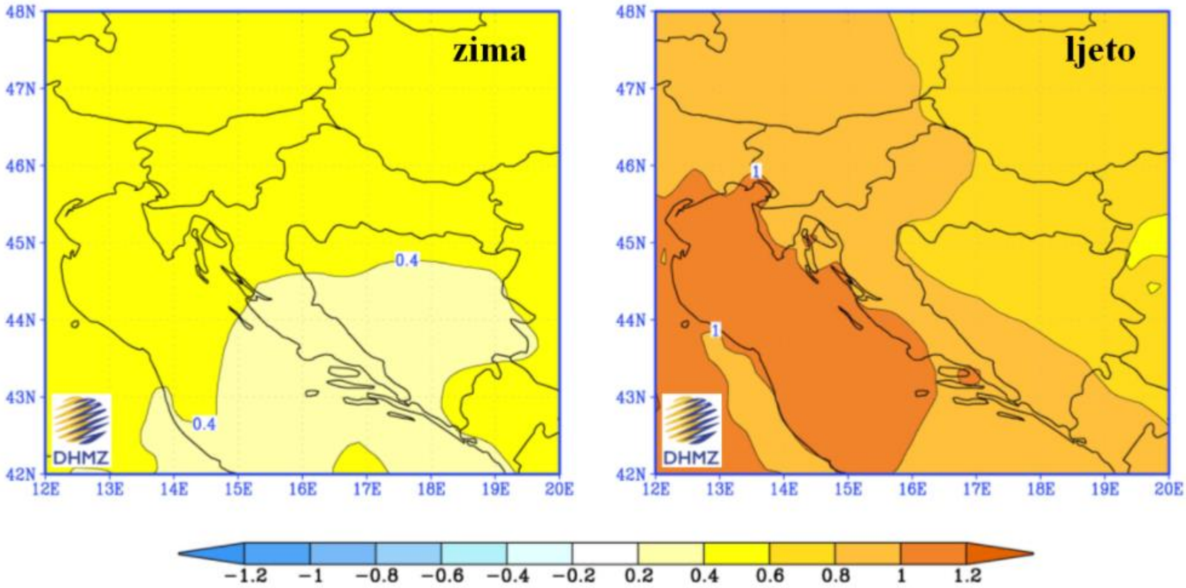


Figure 5 Change in ground air temperature (in ° C) in Croatia in the period 2011-2040 compared to the period 1961-1990 according to the results of the middle class of the RegCM regional climate model ensemble for A2 greenhouse gas emission scenario for winter (left) and summer (right)). [9]

In the second period of the future climate (2041-2070), the expected amplitude of growth in Croatia in winter is up to 2 ° C in the continental part and up to 1.6 ° C in the south, and in summer up to 2.4 ° C in the continental part of Croatia, and up to 3 ° C in the coastal zone [10].

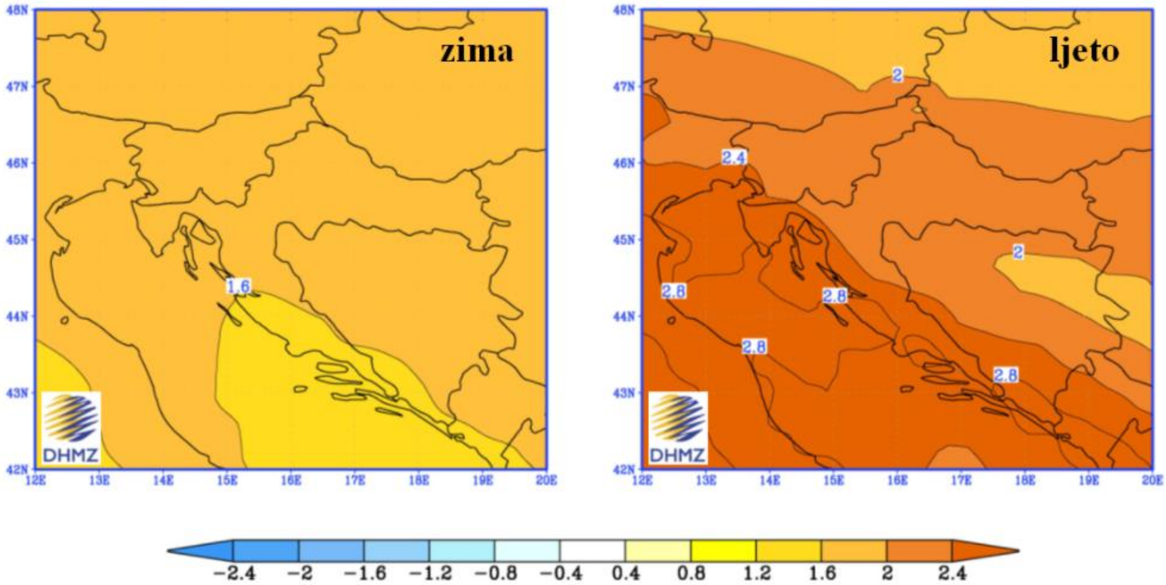


Figure 6 Change in ground air temperature (in ° C) in Croatia in the period 2041-2070 compared to the period 1961-1990 according to the results of the middle class of the RegCM regional climate model ensemble for A2 greenhouse gas emission scenario for winter (left) and summer (right). [9]

The main data source for the World Bank Group's Climate Change Knowledge Portal (CCKP) is the CMIP5 (Coupled Inter-comparison Project No.5) data ensemble. It builds the database for the global climate change projections presented in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC).

Based on World Bank Group's Climate Change Knowledge Portal (CCKP) Croatia is expected to become hotter and drier, especially in the summer. Climate change trends are projected to increase temperatures and decrease water availability across Croatia over this century. Trends in temperature show warming throughout Croatia, with higher temperatures in the mainland than the coast or the Dalmatian areas. Maximum temperatures are expected to see the greatest degree of change, per decade. CCKP data analysis for high emission scenarios, show monthly mean temperature changes increasing by 1.36°C by the 2030s to more than 4°C by the 2090s. Temperature trends will see significant increase in summer months (May to September) as well as winter and spring seasons. Minimum temperatures are projected to experience the largest increase through mid-century. Specific 'new hot spots' are in the northern and western areas of Croatia, the northern regions in Gorski Kotar and the eastern part of Lika during its winter months. The coastal areas will experience the biggest change during summer seasons.

Across all emission scenarios, temperatures will continue to increase for Croatia throughout the end of the century. As seen in Figure 7, under a high-emission scenario, average temperatures will increase rapidly by mid-century. Across the seasonal cycle (Figure 8), temperature increases will spike will be felt from April to June and again in September and October. Increased heat and extreme heat conditions will result in significant implications for public, the agricultural sector and water resources. [11]

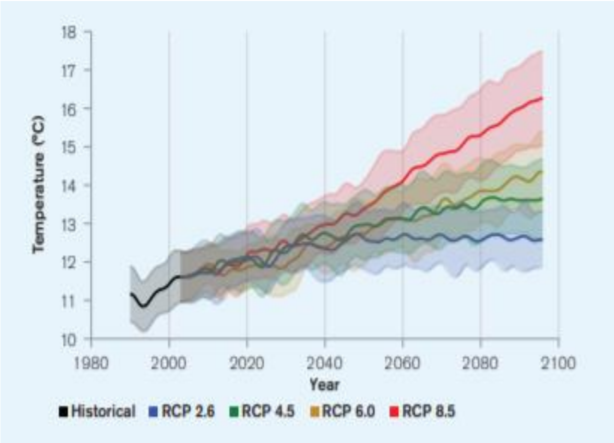


Figure 7 Projected average temperature for Croatia (Reference period 1986-2005) [11]

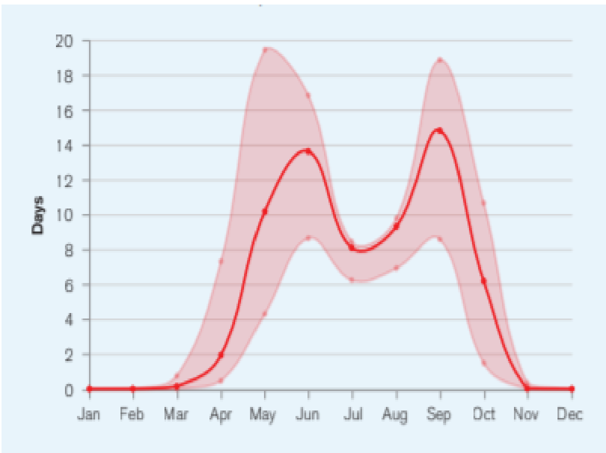


Figure 8 Projected change in summer days (Tmax>25°)(RCP8.5, Ensemble, Reference period 1986-2005) [11]

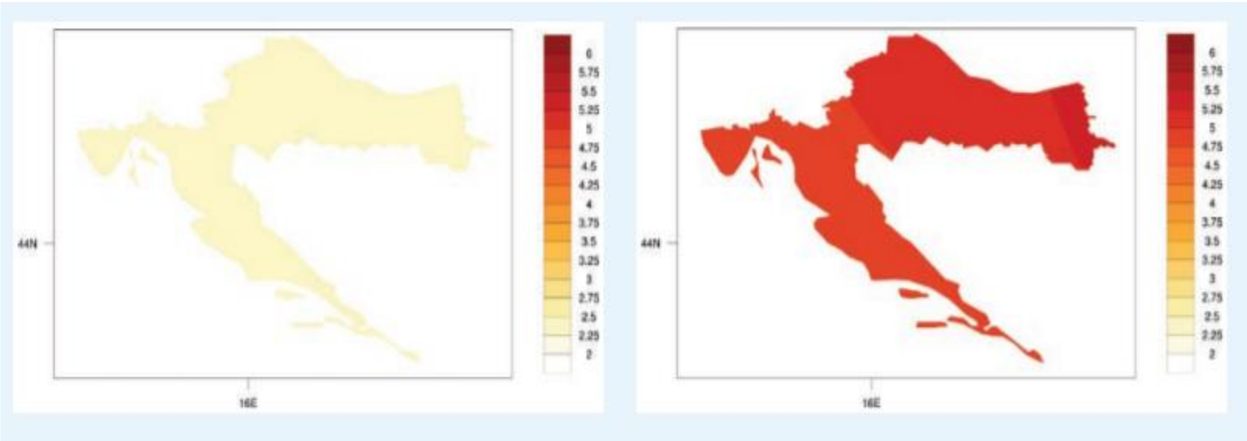


Figure 9 CMIP5 ensemble projected change (32 GCMs) in annual temperature by 2040-2059 (left) and by 2080-2099 (right), relative to 1986-2005 baseline under RCP8.5 [11]

Projected changes in precipitation

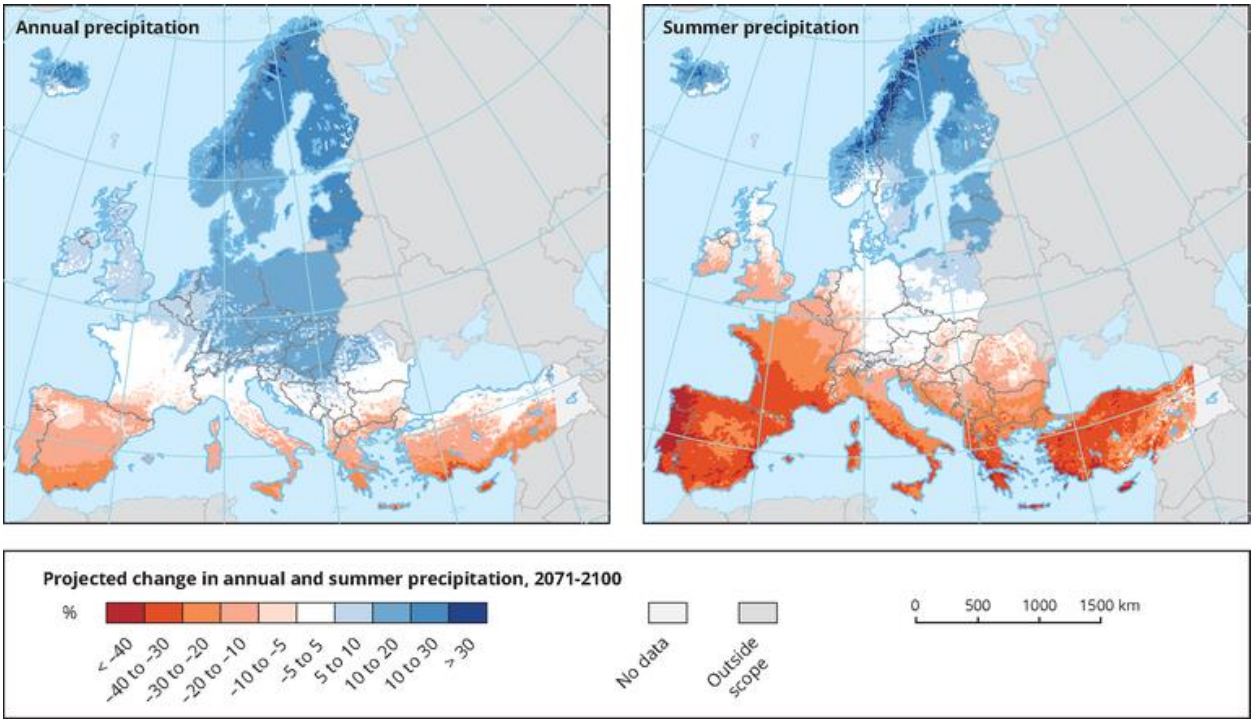


Figure 10 Projected changes in annual (left) and summer (right) precipitation (%) in the period 2071-2100 compared to the baseline period 1971-2000 for the forcing scenario RCP 8.5. Model simulations are based on the multi-model ensemble average of RCM simulations from the EURO-CORDEX initiative. [12]

For a high emissions scenario (RCP8.5), the models project a statistically significant increase in annual precipitation in large parts of central and northern Europe (of up to about 30 %) and a decrease in southern Europe (of up to 40 %) from 1971–2000 to 2071–2100 (Figure 10 left panel). In summer, the precipitation decrease extends northwards (Figure 10 right panel). A zone with small changes that are not significant (but are, however, partially robust in the direction of the change), shows where the precipitation pattern (as presented in the ensemble mean) changes the direction of the change. For a medium emissions scenario (RCP4.5), the magnitude of change is smaller, but the pattern is very similar to the pattern for the RCP8.5 scenario. The range of projected changes in precipitation from the multi-model ensemble are generally the same between RCP4.5 and RCP8.5, or larger in RCP8.5, especially at the end of the century. [12]

Based on DHMZ regional climate model, changes in precipitation in the near future (2011-2040) are very small and limited to smaller areas and vary depending on the season. The largest change in precipitation, according to the A2 scenario, can be expected in the Adriatic in the autumn when RegCM indicates a decrease in precipitation with a maximum of approximately 45-50 mm in the southern part of the Adriatic. However, this decrease in the autumn precipitation is not statistically significant. [9]

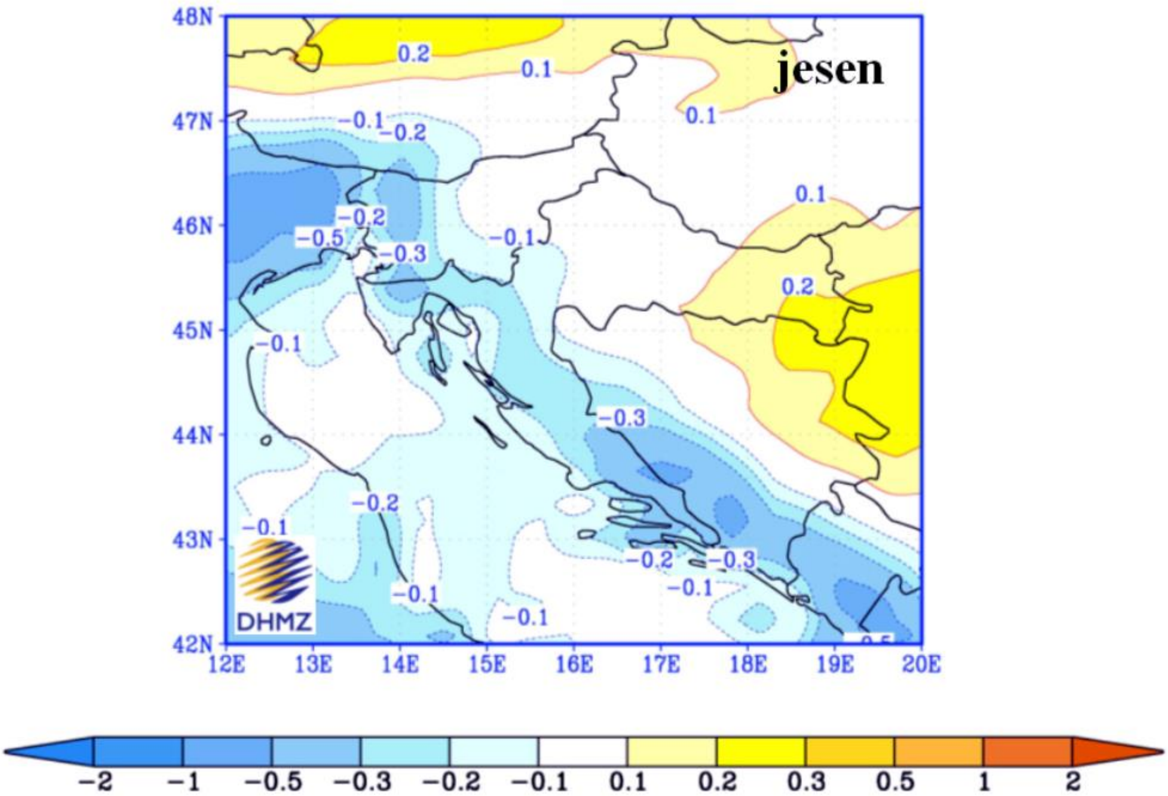


Figure 11 Change in precipitation in Croatia (in mm / day) in the period 2011-2040 compared to the period 1961-1990 according to the results of the regCM regional climate model ensemble for the A2 greenhouse gas emission scenario for autumn. [9]

In the second period of the future climate (2041-2070), precipitation changes in Croatia are more pronounced. Thus, during the summer in mountainous Croatia and in the coastal area, precipitation is expected to decrease. The reductions reach a value of 45 - 50 mm and are statistically significant. In winter, an increase in precipitation can be expected in north-western Croatia and in the Adriatic, but this increase is not statistically significant. [9]

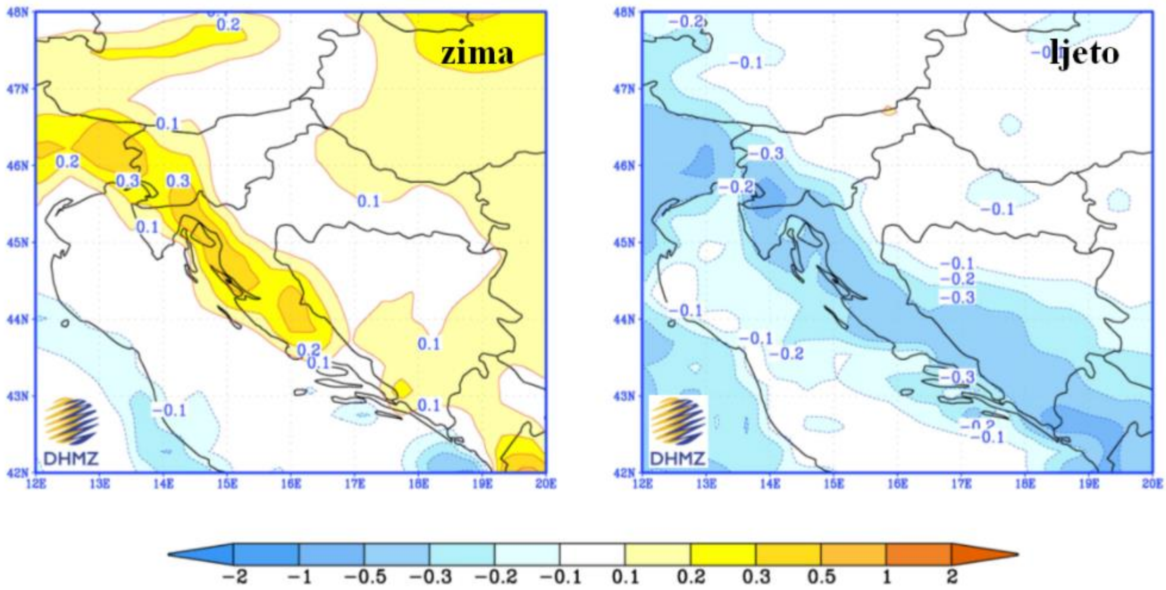


Figure 12 Change in precipitation in Croatia (in mm / day) in the period 2041-2070 compared to the period 1961-1990 according to the results of the middle class of the RegCM regional climate model ensemble for A2 greenhouse gas emission scenario for winter (left) and summer (right). [9]

Based on World Bank Group's Climate Change Knowledge Portal (CCKP) future precipitation trends for Croatia are projected to decline steadily over the century (eastern areas may experience increased rainfall). However, these negative trends are primarily recognized in the summer months in the mountain regions as well as in the Adriatic areas. Annual decreases in precipitation are also expected in Istria and Gorski Kotar, due to reduced spring rainfall. An increased number of consecutive dry days are expected to be seen over the spring season for the northern Adriatic, with summer seasons seeing an extended number of dry days reach the southern coast of Croatia. Through the mid-century, the largest decrease (just over 10 %) will be in the spring in the southern areas of Dalmatia and in the summer (10–15%) in the mountainous areas and in northern Dalmatia. The largest increase in total precipitation, 5–10 %, is expected on the islands in autumn and in northern Croatia in winter. Figure 7 shows the change in the projected annual average precipitation for Croatia. At a nationally aggregated scale, mean annual precipitation for the country is expected to remain largely similar; however, at regional scales, western and specifically southern areas are expected to experience the most significant reduction in precipitation. [11]

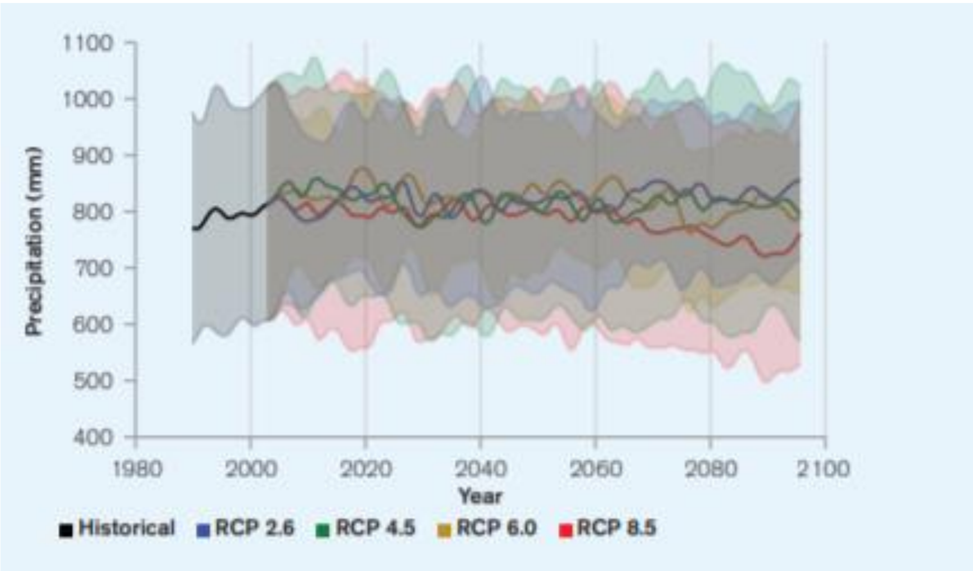


Figure 13 Projected annual average precipitation in Croatia (Reference period 1986-2005) [11]

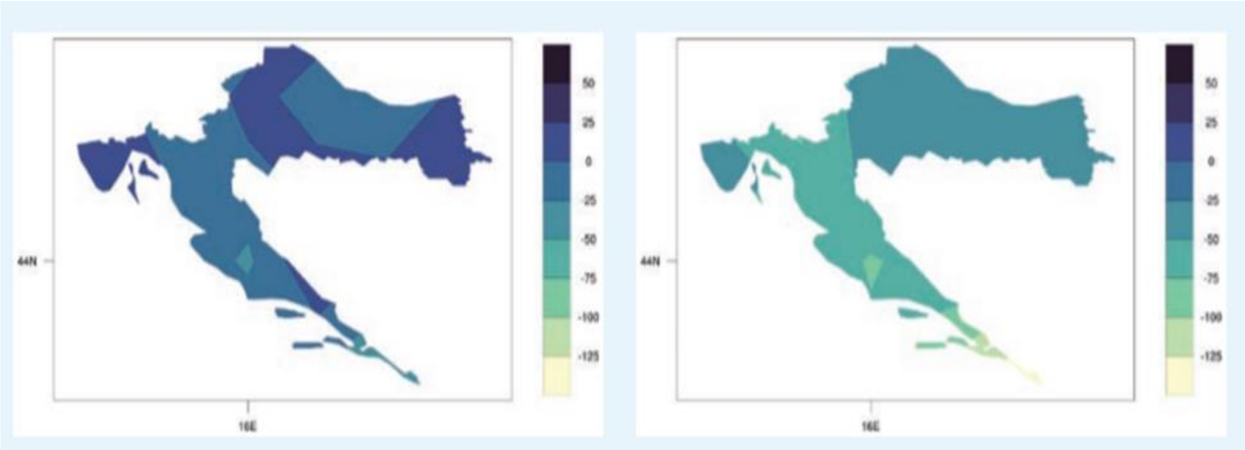


Figure 14 CMIP5 ensemble projected change (32 GCMs) in precipitation (bottom) by 2040-2059 (left) and by 2080-2099 (right), relative to 1986-2005 baseline under RCP8.5 [11]

Projected changes in sea level

Based on EEA global mean sea level (GMSL) has risen about 21 cm since 1900, at an accelerating rate. GMSL reached its highest value ever in 2020. GMSL will likely rise by 0.28-0.55 m under a very low emissions scenario (SSP1-1.9) and 0.63-1.02 m under a very high emissions scenario (SSP5-8.5) by 2100, relative to the 1995-2014 average. GMSL simulations that include the possibility of fast disintegration of the polar ice sheets project a rise of up to 5m by 2150. Most coastal regions in Europe have experienced an increase in sea level relative to land, except for the northern Baltic Sea coast. [13]

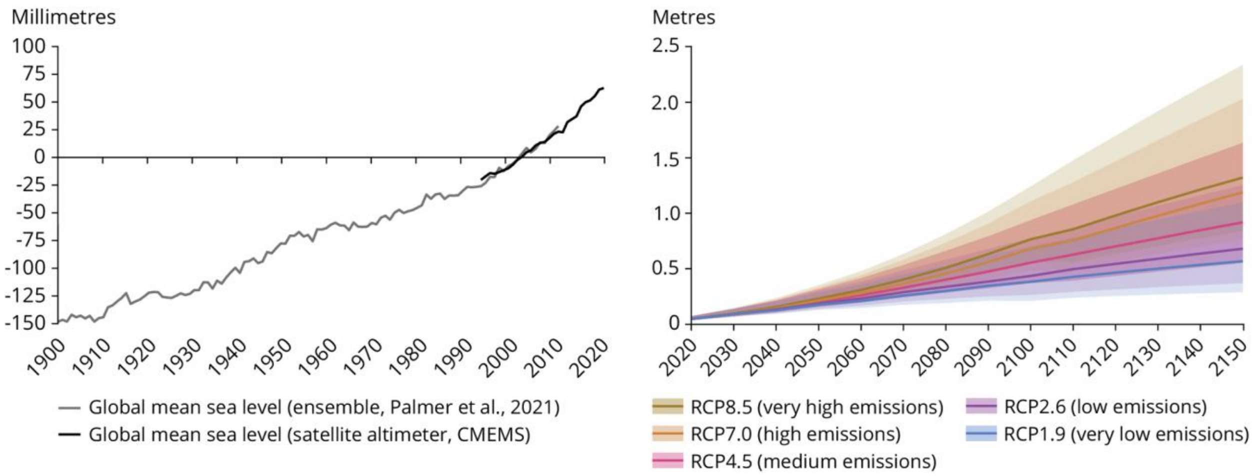
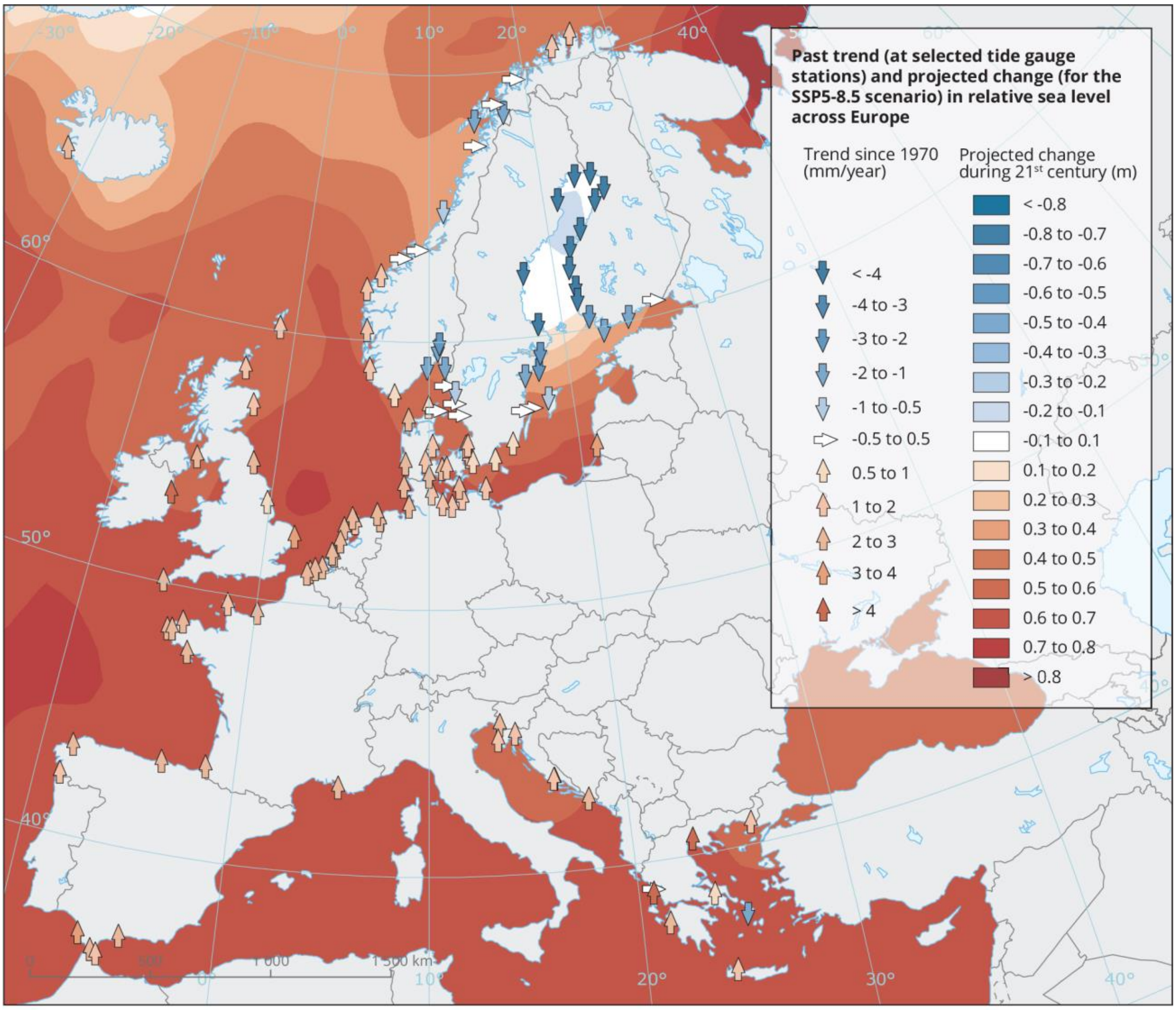


Figure 15 Observed and projected change in global mean sea level [13]



Reference data: ©ESRI

Figure 16 Past trend and projected change in relative sea level across Europe [13]

The IPCC projections of sea level include estimates of contributions from:

- Ocean thermal expansion
- Glacier mass loss
- Greenland and Antarctic ice sheet surface mass balance (net change from the addition of mass through precipitation and loss through melting) and dynamic processes such as collapse of ice shelves
- Changes in land water storage (dams and ground water storage) [14]

Based on IPCC, GMSL will rise between 0.43 m (0.29–0.59 m, RCP2.6) and 0.84 m (0.61–1.10 m, RCP8.5) by 2100 relative to 1986–2005. Beyond 2100, sea level will continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the GIS and AIS and will remain elevated for thousands of years. Under RCP8.5, the rate of sea level pressure will be 15 mm/yr (10–20 mm/yr) in 2100, and could exceed several cm/yr in the 22nd century. [15]

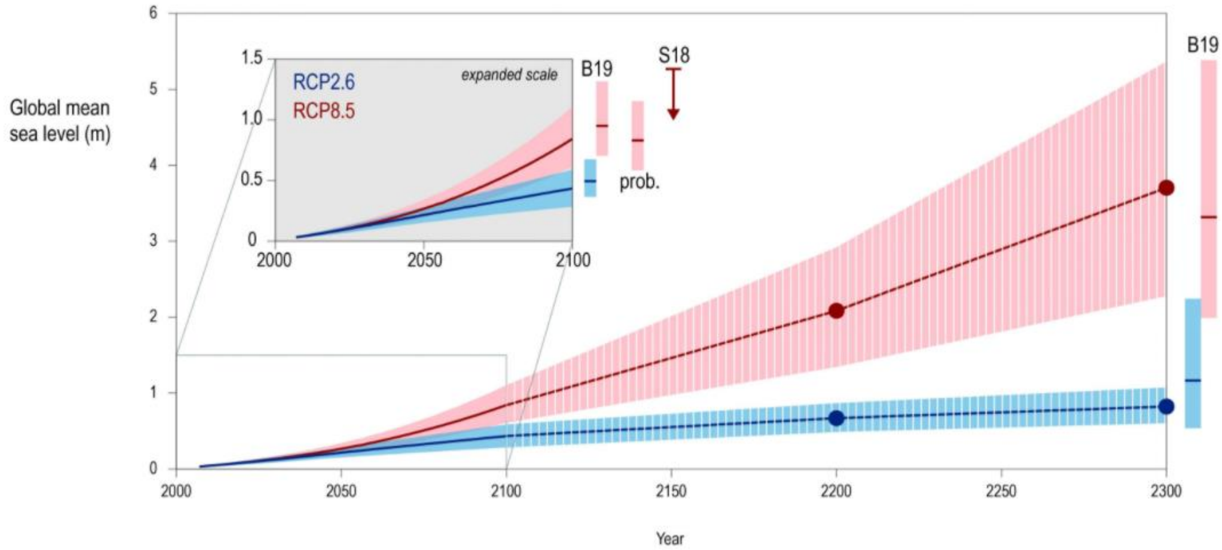


Figure 17 Projected sea level rise (SLR) until 2300 [15]

The inset shows an assessment of the likely range of the projections for RCP2.6 and RCP8.5 up to 2100. Projections for longer time scales are highly uncertain but a range is provided.

In the Republic of Croatia, sea level measurements are carried out at tide gauge stations in Dubrovnik, Split, Zadar, Bakar and Rovinj (Figure 18).

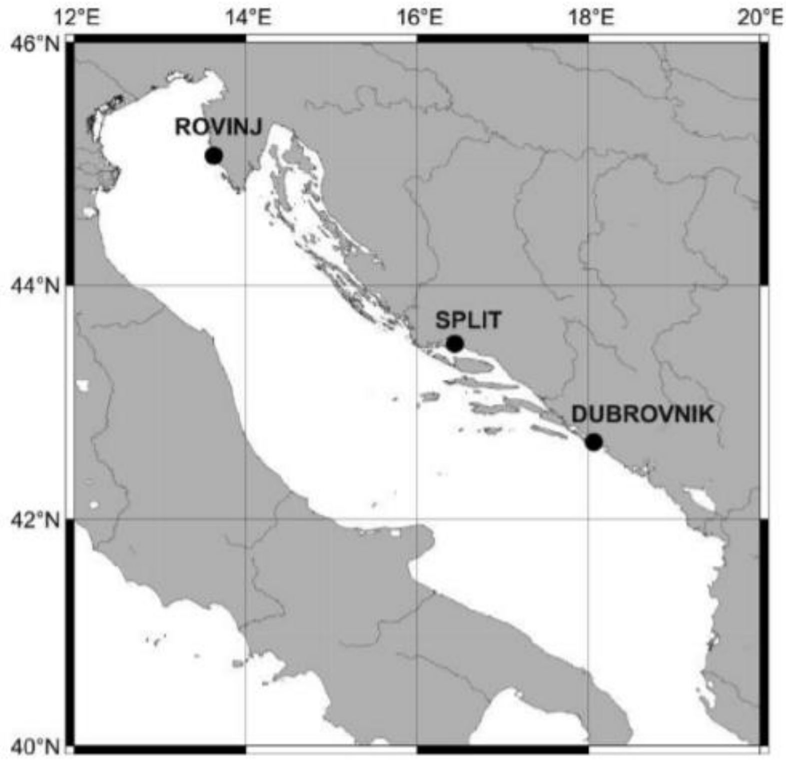


Figure 18 Tide gauge stations in Croatia

The mid-sea level rise test was performed using methods of linear regression analysis. Statistical analysis of average annual values of sea level from 1955 to 2009 indicates a trend of sea level rise from 0.5 to 0.8 mm / year. [16]

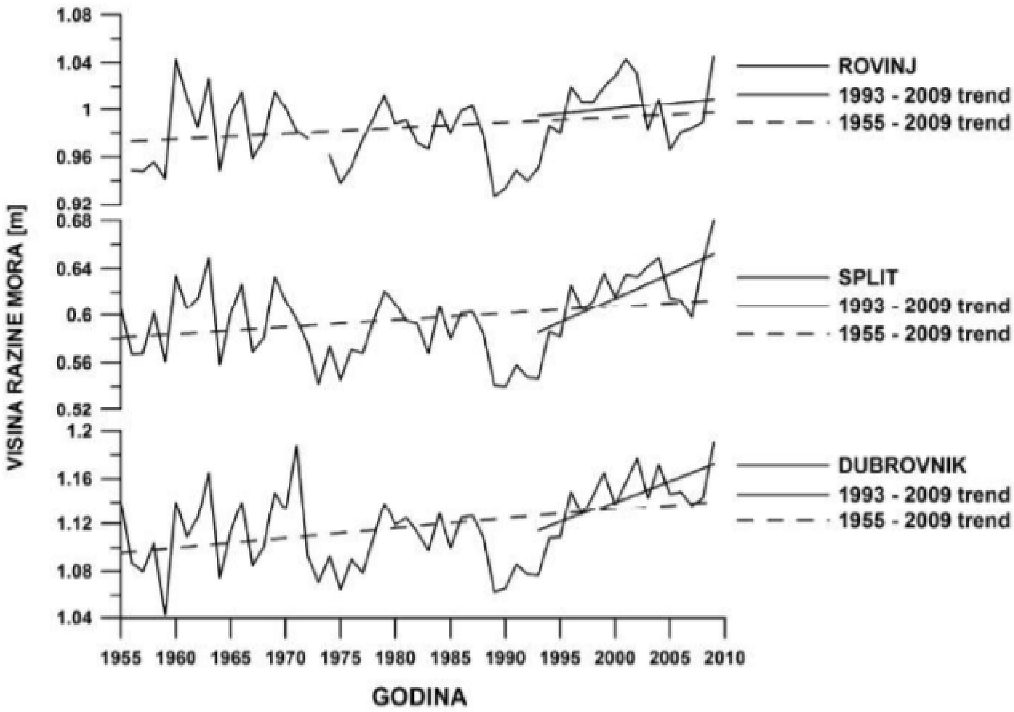


Figure 19 Annual mean sea level values with linear upward trends for Rovinj, Split and Dubrovnik [16]

Analysing the measured values of the mean sea level after 1993, it is possible to observe the trend of accelerated increase of the mean sea level, which is especially pronounced in Split (4.2 mm / year) and Dubrovnik (3.6 mm / year). If this trend continues in the central and southern Adriatic, it would mean an increase in sea level of about 40 cm over the next hundred years, which is in line with IPCC forecasts, which estimate that global sea level rise from 2000 to 2100 is between 20 and 50 cm. [16]

Vulnerability maps - methodology

Groundwater is the main reservoir of available freshwater used and it is the primarily water source for more than two billion people [17]. It encompasses 70% of domestic water use in the European union [18] and it is a source for half or more of the irrigation water used for world's food production [19]. Seawater intrusion (SWI) represents both natural and anthropogenic induced process where saltwater from sea diffuses into coastal aquifers. Coastal aquifers are already highly vulnerable environment, which are further endangered by the climate changes like sea level rise and reduced precipitation.

Based on the vulnerability indices, several methods for aquifer groundwater vulnerability assessment were proposed: Aquifer Vulnerability Index (AVI) [20], DRASTIC [21], GALDIT [22, 23] and SINTACS [24]. Of the methods, the GIS-based GALDIT method was primarily developed for coastal aquifers. Therefore, in determining the lower river Neretva aquifer vulnerability to seawater intrusion, a modified GALDIT method was applied.

The acronym GALDIT [22] is formed from six vulnerability factors (indices):

- **G**roundwater Occurrence (aquifer type; unconfined, confined and leaky confined),
- **A**quifer Hydraulic Conductivity,
- Height of Groundwater **L**evel above Sea Level,
- **D**istance from the Shore (distance inland perpendicular from shoreline),
- **I**mpact of existing status of seawater intrusion in the area and
- **T**hickness of the aquifer, which is being mapped.

Calculated GALDIT factors are then forwarded to the numerical ranking system that consists of three parts: one weight per indicator, four ranges and corresponding importance ratings per indicator (Table 2).

Table 2 Numerical ranking system for GALDIT indicators [23]

GALDIT Indicator	Weight (W)	Range		Importance Rating (IR)
Groundwater Occurrence	1	Confined aquifer		10.0
		Unconfined aquifer		7.5
		Leaky confined aquifer		5.0
		Bounded aquifer (recharge and/or impervious boundary aligned parallel to the coast)		2.5
Aquifer Hydraulic Conductivity (m/day)	3	High	>40	10.0
		Medium	10-40	7.5
		Low	5-10	5.0
		Very low	<5	2.5
Height of Groundwater Level above Mean Sea Level (m)	4	High	<1.0	10.0
		Medium	1.0-1.5	7.5
		Low	1.5-2.0	5.0
		Very low	>2.0	2.5
Distance from the Shore/High Tide (m)	4	High	<500	10.0
		Medium	500-750	7.5
		Low	750-1000	5.0
		Very low	>1000	2.5
Impact of existing status of seawater intrusion, $Cl^-/[HCO_3^{-1}+CO_3^{2-}]$ (epm)	1	High	>2.0	10.0
		Medium	1.5-2.0	7.5
		Low	1.0-1.5	5.0
		Very low	<1	2.5
Thickness of the (saturated) aquifer (m)	2	High	>10	10.0
		Medium	7.5-10	7.5
		Low	5.0-7.5	5.0
		Very low	<5.0	2.5

The GALDIT vulnerability index is determined as weighted average of the six GALDIT indicators importance ratings:

$$GALDIT - Index = \frac{\sum_{i=1}^{6}(W_i \times IR_i)}{\sum_{i=1}^{6} W_i}$$

The final decision criteria for classification of the coastal areas into three seawater intrusion vulnerability categories is suggested by Chachadi and Lobo Ferreira [23] (Table 3).

Table 3 GALDIT-Index vulnerability categories [23]

Vulnerability category	GALDIT-Index
High	>7.5
Moderate	5.0-7.5
Low	<5.0

Determination of GALDIT Indices for the lower river Neretva aquifer

The lower river Neretva valley basically consists of two vertically stratified aquifers, separated by thick clay layer. The deeper aquifer thus being confined, and the upper one unconfined. In assessing the lower river Neretva vulnerability to saltwater intrusion, only upper unconfined aquifer was analysed as it is the crucial aquifer for agricultural production.

Groundwater occurrence (G)

The groundwater occurrence is characterized by aquifer type [23]: confined, unconfined, leaky confined or limited by one or more boundaries. The observed aquifer in the lower river Neretva valley is unconfined, therefore a importance rating of 7.5 is given (Figure 20).

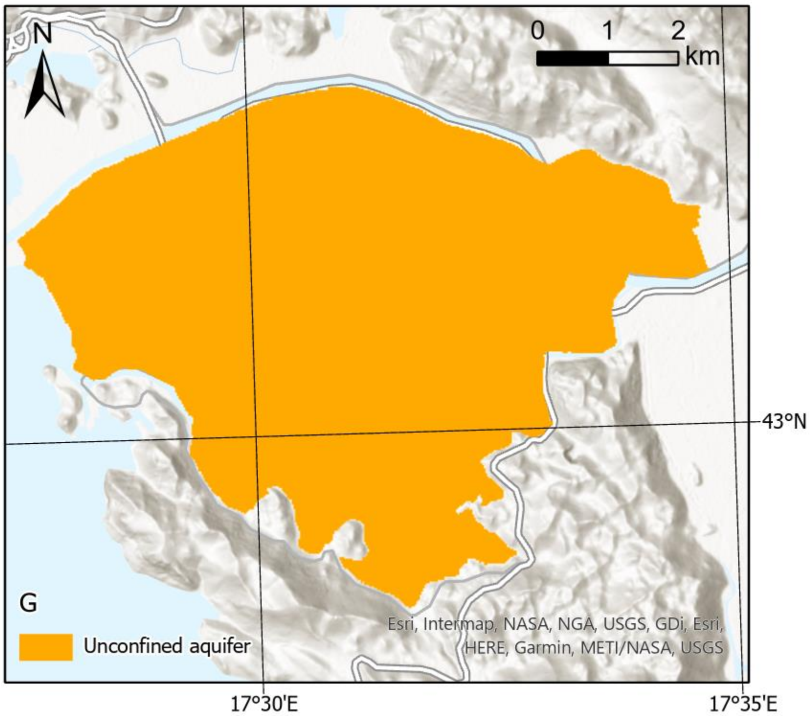
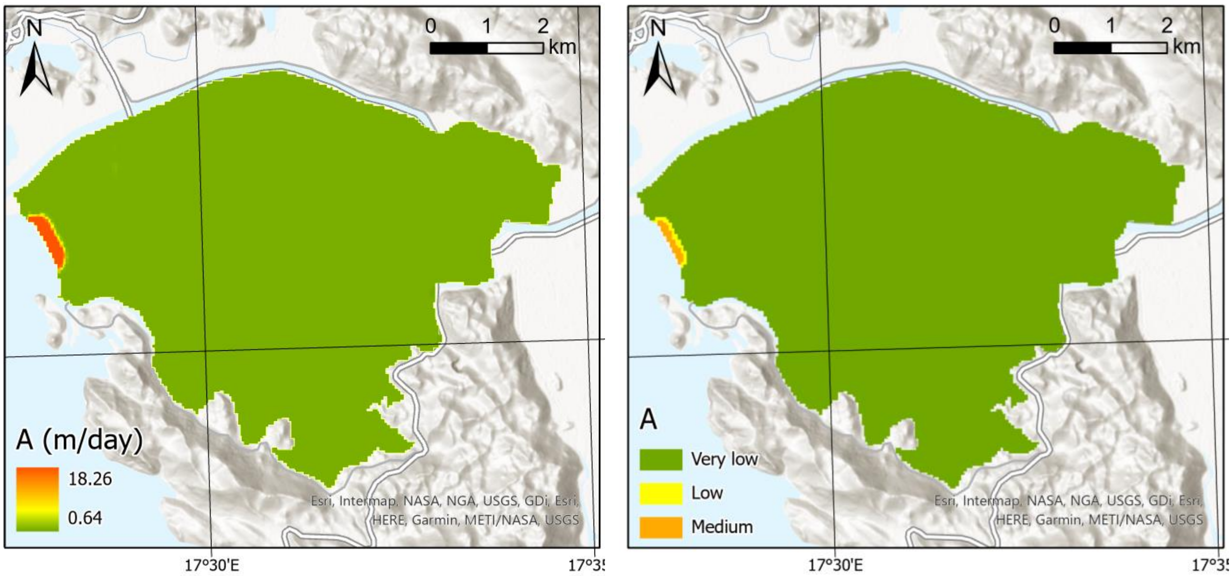


Figure 20 Groundwater occurrence (G) GALDIT indicator for lower river Neretva aquifer.

Aquifer hydraulic conductivity (A)

Aquifer hydraulic conductivity refers to ability of an aquifer to transmit water. It is a hydrodynamic parameter that is used to express rate of flow of water in the aquifer. In the light of saltwater intrusion, aquifer hydraulic conductivity is proportional to the inland reach of the seawater. Furthermore, high hydraulic conductivity results in wider cone of depression. The lower river Neretva aquifer hydraulic conductivity data was primarily derived from lithological logs. Then, the point data was transformed to 2D raster field data using geostatistical interpolation techniques (Figure 21a). In this work, the ranges and importance ratings presented in Table 2 were adopted to determine GALDIT indicator classes (Figure 21b).



(a) (b)

Figure 21 Aquifer hydraulic conductivity (A) GALDIT indicator for lower river Neretva aquifer: 2D raster field expressed in m/day (a), classified 2D field by ranges and indicator ratings listed in numerical ranking system (Table 2) (b).

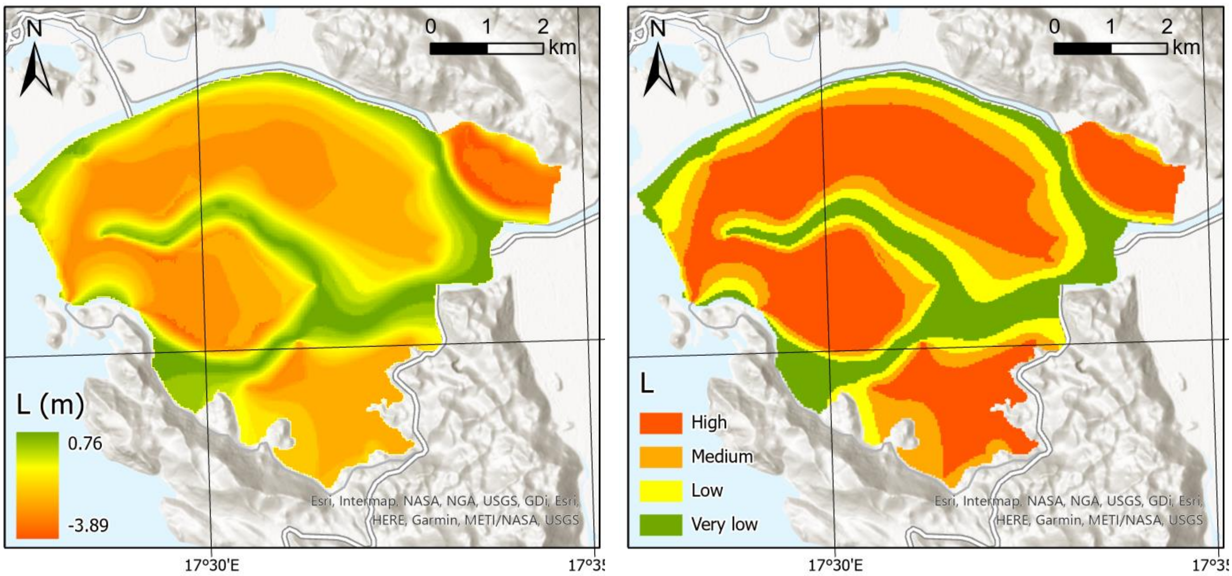
Height of Groundwater Level above Sea Level (L)

The height difference between groundwater level and the mean sea level is important seawater intrusion indicator as it defines the hydraulic pressure availability to push back the seawater front. Following Ghyben-Herzberg relation, for every meter of freshwater above mean sea level there are 40 meters of freshwater below it (to the freshwater-seawater interface).

The height difference between groundwater level and the mean sea level for lower river Neretva aquifer was derived from piezometric head readings and tide gauge data. These point data were transformed to 2D raster data using probabilistic interpolation method (Empirical Bayesian Kriging) (Figure 22a). Due to the specific configuration of the pilot site, a modified ranges for GALDIT L indicator were implemented (Table 4, Figure 22b).

Table 4 Modified ranges and corresponding importance ratings for Height of Groundwater Level above Mean Sea Level (m) GALDIT (L) indicator

Vulnerability category	Height of Groundwater Level above Mean Sea Level (m)	Importance Rating
High	<-1.75	10.0
Moderate	-1.75 – -1.00	7.5
Low	-1.00 – -0.25	5.0
Very low	>-0.25	2.5



(a) (b)

Figure 22 Height of Groundwater Level above Sea Level (L) GALDIT indicator for lower river Neretva aquifer: 2D field expressed in m (a), classified 2D field by ranges and indicator ratings listed in modified numerical ranking system (Table 4Table 2) (b).

Distance from the Shore (D)

Seawater intrusion generally decreases while moving inlands at right angles to the shore line and the creek. The highest vulnerability is in the area close to the shore and the creek. For the lower river Neretva aquifer, along the GALDIT D indicator (here named SAD – saltwater distance), GALDIT method was expanded for one more indicator: distance from freshwater.

SAD indicator is reconstructed as perpendicular Euclidean distance to river Neretva mouth from north (confirmed as source of seawater intrusion, especially in dry season), shore line from the east (Adriatic sea) and lateral channel that surrounds the valley from south (Figure 23a). Due to the specific configuration of the pilot site, a modified ranges for GALDIT SAD (D) indicator were implemented (Table 5, Figure 23b).

Table 5 Modified ranges and corresponding importance ratings for Distance from the saltwater (m) GALDIT (SAD) indicator

Vulnerability category	Distance from the saltwater (SAD) (m)	Importance Rating
High	<750	10.0
Moderate	750-1500	7.5
Low	1500–2250	5.0
Very low	>2250	2.5

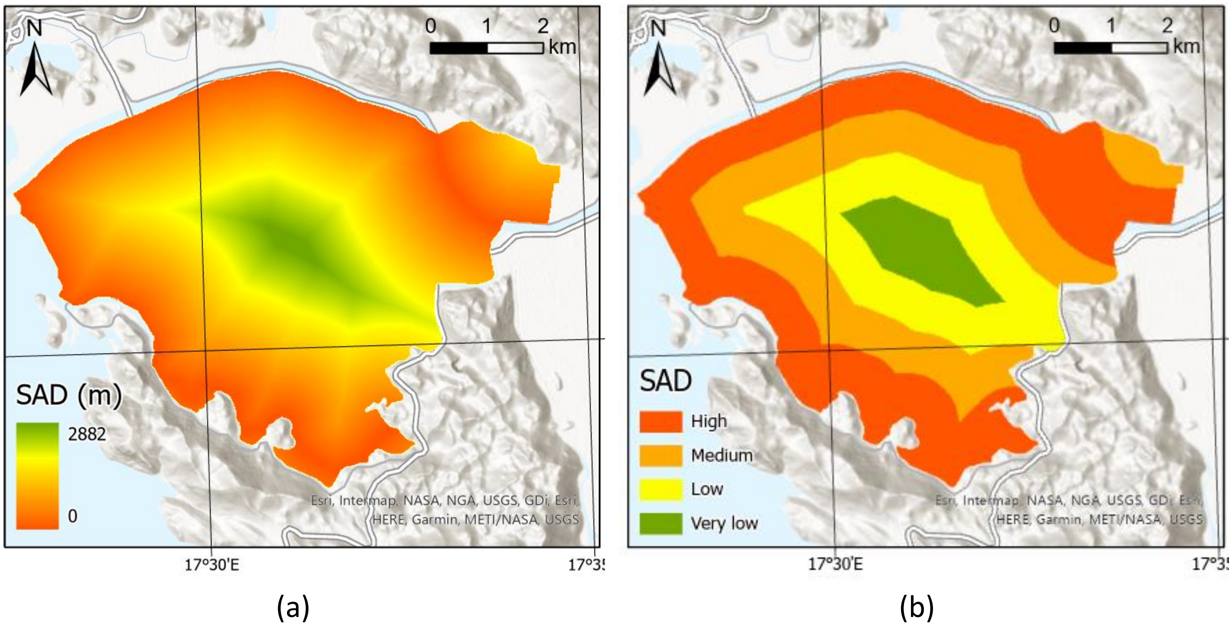


Figure 23 Distance from saltwater (SAD) GALDIT indicator for lower river Neretva aquifer: 2D field expressed in m (a), classified 2D field by ranges and indicator ratings listed in modified numerical ranking system (Table 5Table 2) (b).

The lower river Neretva valley is primarily used for intensive agricultural production. The area was transformed from swamp to highly fertile soil area by extensive soil amelioration and land reclamation works that started in 1960s. Therefore, the valley is criss-crossed with dense network of channels used for both drainage and irrigation, which may (but not always) be source of freshwater for irrigation and salinity risk mitigation or reduction. FRD indicator is reconstructed as perpendicular Euclidean distance to main channels of drainage/irrigation network (Figure 24a). Seawater intrusion is inversely proportional to distance from freshwater (FRD), but the reach of the FRD may be seen as much lower than the SAD (Table 5 and Table 6). Suggested ranges for GALDIT FRD indicator are shown in Table 6 and were implemented on Figure 24b.

Table 6 Ranges and corresponding importance ratings for Distance from the freshwater (m) GALDIT (FRD) indicator

Vulnerability category	Distance from the freshwater (FRD) (m)	Importance Rating
High	>200	10.0
Moderate	100–200	7.5
Low	50–100	5.0
Very low	<50	2.5

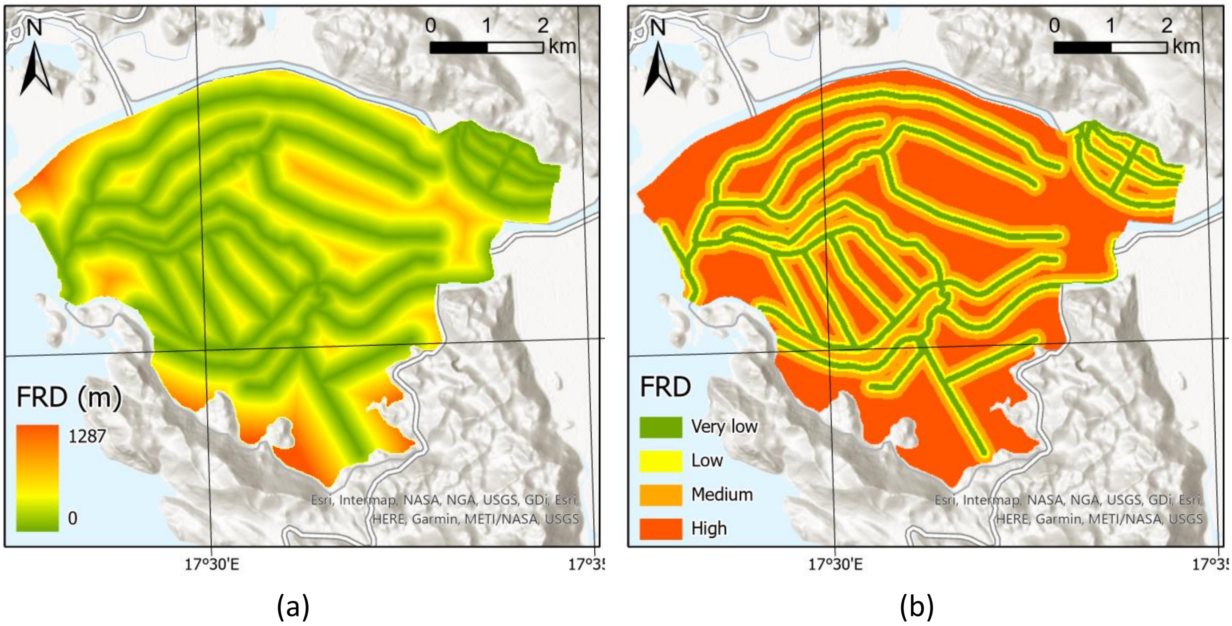


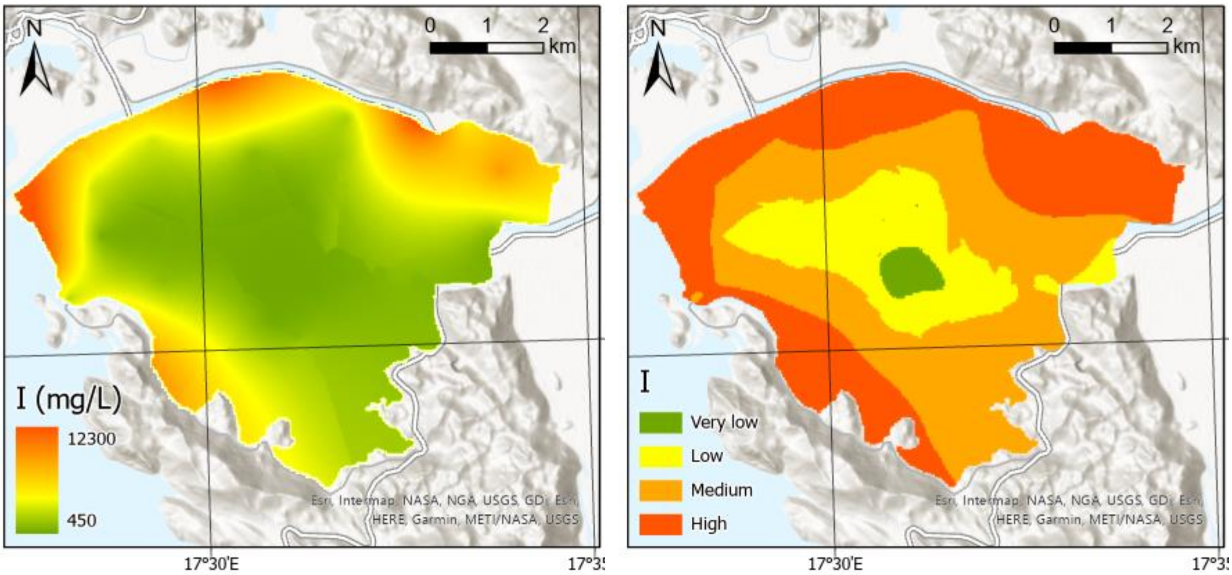
Figure 24 Distance from freshwater source (FRD) modified GALDIT indicator for lower river Neretva aquifer: 2D field expressed in m (a), classified 2D field by ranges and indicator ratings listed in modified numerical ranking system (Table 6Table 2) (b).

Impact of existing status of seawater intrusion (I)

For estimating the impact of existing status of seawater intrusion (I), Chachadi and Lobo Ferreira [23] recommended the ratio of $Cl^-/[HCO_3^{-1}+CO_3^{2-}]$ as GALDIT indicator. In this work, instead of the proposed parameter, a Total Dissolved Solids (TDS) in mg/L was selected as GALDIT (I) indicator. TDS is a measure of the dissolved combined content of all inorganic and organic substances present in a liquid, i.e., the total concentration of dissolved substances in water. The data was derived from geochemical analysis data of water samples. The point data was transformed to 2D raster field by probabilistic interpolation method (Empirical Bayesian Kriging), as shown on Figure 25a. In order to provide meaningful classification needed for GALDIT method, a groundwater classification based on TDS by Vetrimurugan, Elango and Rajmohan [25] was implemented (Table 7, Figure 25b). Groundwater classification based on TDS [25] is selected because it provides relation to adequate water quality for irrigation purposes, which is the main source of groundwater withdrawal in the lower river Neretva aquifer.

Table 7 Ranges and corresponding importance ratings for Impact of existing status of seawater intrusion GALDIT (I) indicator and groundwater classification based on TDS [25]

Vulnerability category	Water type [25]	Impact of existing status of seawater intrusion (I) TDS (mg/L)	Importance Rating
High	Unfit for drinking and irrigation	>3000	10.0
Moderate	Useful for irrigation	1000–3000	7.5
Low	Permissible for drinking	500–1000	5.0
Very low	Desirable for drinking	<500	2.5



(a) (b)

Figure 25 Impact of existing status of seawater intrusion (I) GALDIT indicator for lower river Neretva aquifer: 2D field expressed in mg/L (a), classified 2D field by ranges and indicator ratings listed in modified numerical ranking system (Table 7Table 2) (b).

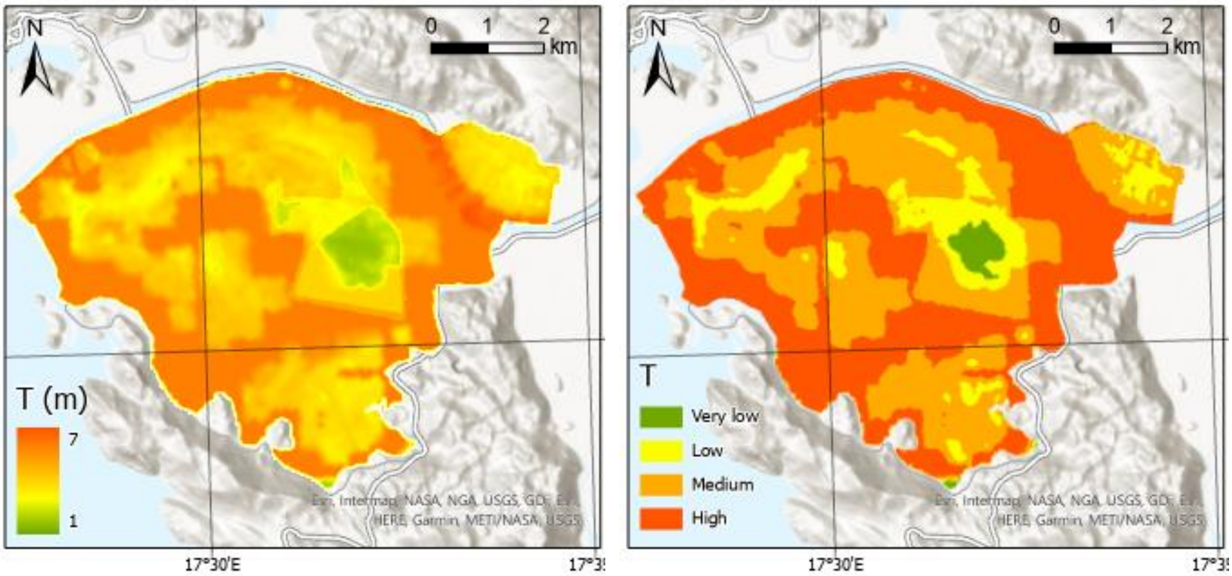
Thickness of the aquifer (T)

Thickness of the unconfined aquifer is essential in determining the area and scale of seawater intrusion in coastal zones. Seawater intrusion is proportional to the thickness of the aquifer. The lower river Neretva aquifer thickness was determined from the lithological logs data, which were the then interpolated by geostatistical methods to derive 2D raster field data (Figure 26a). Due to the specific configuration of the pilot site, a modified ranges for GALDIT (T) indicator were implemented (

able 8, Figure 26b).

able 8 Ranges and corresponding importance ratings for Thickness of the aquifer (m) GALDIT (T) indicator

Vulnerability category	Thickness of the aquifer (T) (m)	Importance Rating
High	>5.0	10.0
Moderate	3.5–5.0	7.5
Low	2.0–3.5	5.0
Very low	<2.0	2.5



(a) (b)

Figure 26 Thickness of the aquifer (T) GALDIT indicator for lower river Neretva aquifer: 2D field expressed in m (a), classified 2D field by ranges and indicator ratings listed in modified numerical ranking system (

able 8Table 2) (b).

GALDIT index for the lower river Neretva aquifer

As it is described in previous sections, for some GALDIT indicators, their weights and ranges were adopted from the original publication of Chachadi and Lobo Ferreira [23] (G and A), for some indicators only ranges were tuned (L, T, SAD), one new indicator was added (FRD) and one new range and parameter were adopted (I). The GALDIT vulnerability index is presented on Figure 27, and final table with vulnerability indices and corresponding numerical ranking system is documented in Table 9.

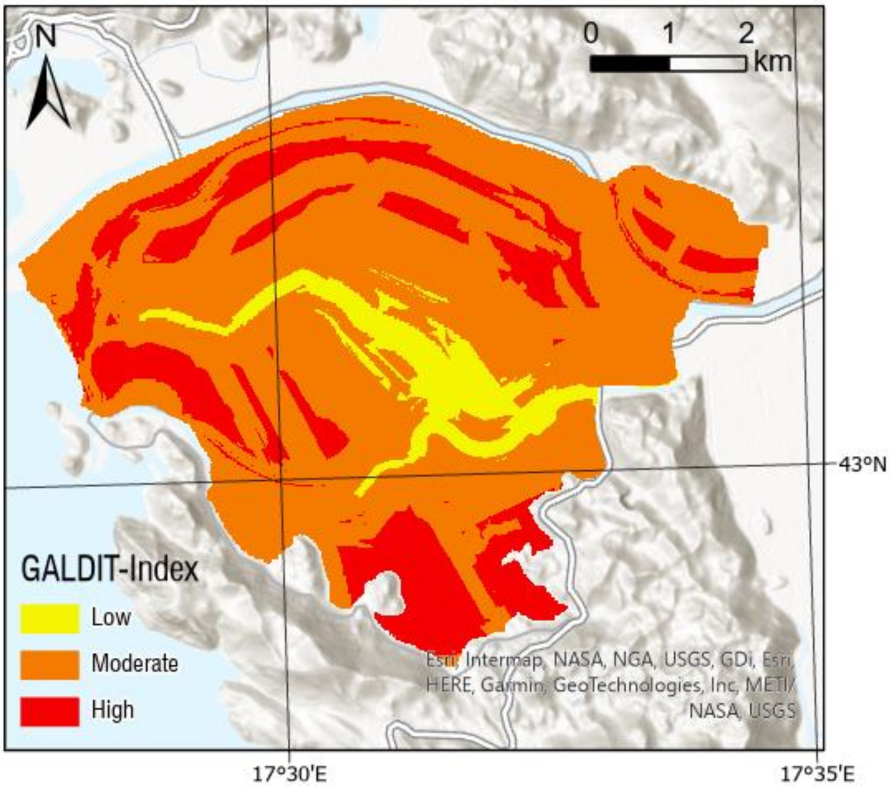


Figure 27 GALDIT index calculated using the weights and indicator ratings displayed in Table 9, and classified by the GALDIT-Index vulnerability categories from Table 3

Table 9 Numerical ranking system of modified GALDIT indicators for lower river Neretva aquifer

(modified) GALDIT Indicator	Weight (W)	Range		Importance Rating (IR)
Groundwater Occurrence (G)	1	Confined aquifer		10.0
		Unconfined aquifer		7.5
		Leaky confined aquifer		5.0
		Bounded aquifer		2.5
Aquifer Hydraulic Conductivity (A) (m/day)	3	High	>40	10.0
		Medium	10-40	7.5
		Low	5-10	5.0
		Very low	<5	2.5
Height of Groundwater Level above Mean Sea Level (L) (m)	4	High	<-1.75	10.0
		Medium	-1.75 – -1.00	7.5
		Low	-1.00 – -0.25	5.0
		Very low	>-0.25	2.5
Distance from the saltwater (SAD) (m)	4	High	<750	10.0
		Medium	750–1500	7.5
		Low	1500–2250	5.0
		Very low	>2250	2.5
Distance from the freshwater (FRD) (m)	3	High	>200	10.0
		Medium	100–200	7.5
		Low	50–100	5.0
		Very low	<50	2.5
Impact of existing status of seawater intrusion, TDS (mg/L)	1	High	>3000	10.0
		Medium	1000–3000	7.5
		Low	500–1000	5.0
		Very low	<500	2.5
Thickness of the (saturated) aquifer (m)	2	High	>5.0	10.0
		Medium	3.5–5.0	7.5
		Low	2.0–3.5	5.0
		Very low	<2.0	2.5

Climate changes impact assessment by modified GALDIT index

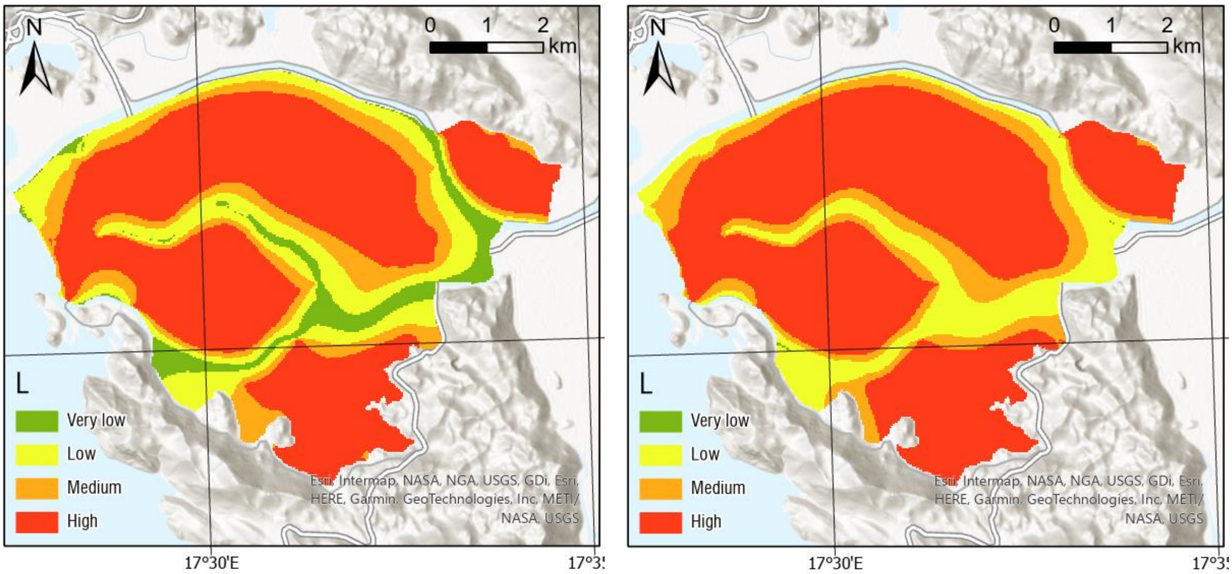
Mean sea level rise

In assessing the climate changes effects to saltwater intrusion in lower Neretva river aquifer, two climate change scenarios were simulated based on IPCC (The Intergovernmental Panel on Climate Change) predictions that by 2100 mean sea level will rise between:

- 0.43 m (0.29–0.59 m, RCP2.6) and
- 0.84 m (0.61–1.10 m, RCP8.5).

Sea level rise will directly impact Height of the Groundwater Level above Sea Level GALDIT L indicator and thickness of the (saturated) aquifer GALDIT T indicator.

Modified ranges for GALDIT L indicator were implemented in assessment of climate changes (Table 4, Figure 28a,b). In comparison with Figure 22b, a substantial increase of low, moderate and high vulnerability area and decrease of very low vulnerability area, that disappears in the less optimistic scenario (Figure 28b).

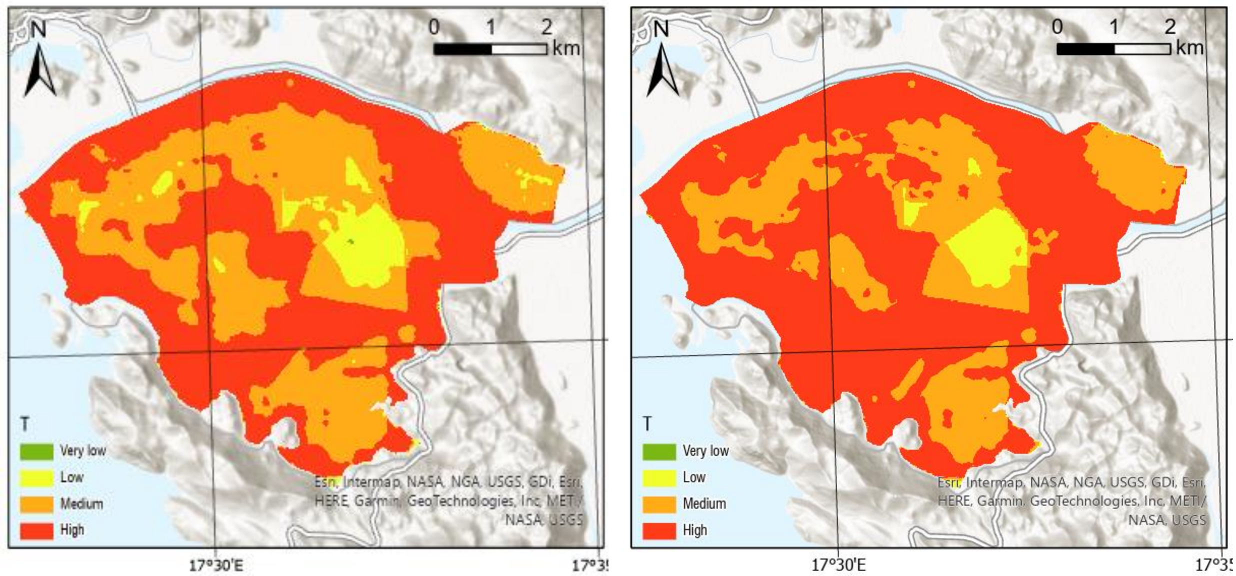


(a) (b)

Figure 28 Height of Groundwater Level above Sea Level (L) GALDIT indicator for lower river Neretva aquifer: result for RCP 2.6 sea level rise scenario of 0.43 m (a), result for RCP 8.5 sea level rise scenario of 0.84 m Table 2(b).

Modified ranges for GALDIT T indicator were also implemented in assessment of climate changes (

able 8, Figure 29a,b). In comparison with Figure 26b, a substantial increase of moderate and high vulnerability area and decrease of very low vulnerability area, that completely disappears in the RCP8.5 scenario (Figure 29b).



(a) (b)

Figure 29 Thickness of the aquifer (T) GALDIT indicator for lower river Neretva aquifer: result for RCP 2.6 sea level rise scenario of 0.43 m (a), result for RCP 8.5 sea level rise scenario of 0.84 m Table 2(b).

Modified GALDIT vulnerability index for two selected climate change scenarios is presented on Figure 30 (RCP 2.6) and Figure 31 (RCP 8.5). It was determined as weighted average of the seven modified GALDIT vulnerability indices whose corresponding numerical ranking system is documented in Table 9.

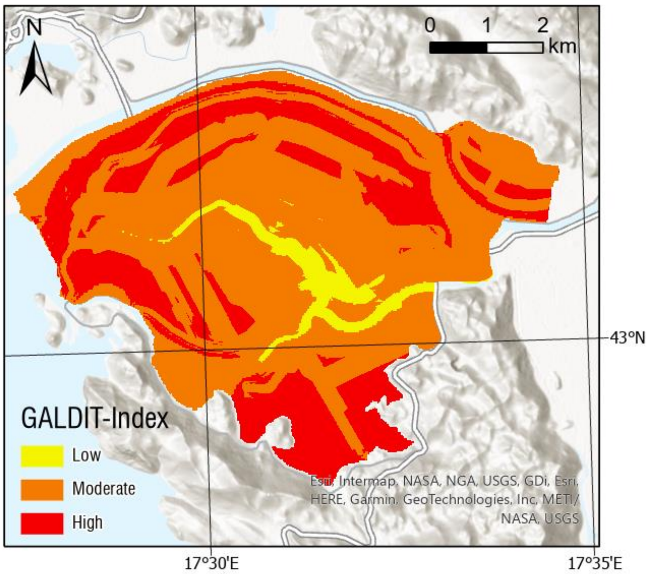


Figure 30 GALDIT index calculated using the weights and indicator ratings displayed in Table 9, and classified by the GALDIT-Index vulnerability categories from Table 3 for RCP 2.6 sea level rise scenario of 0.43 m.

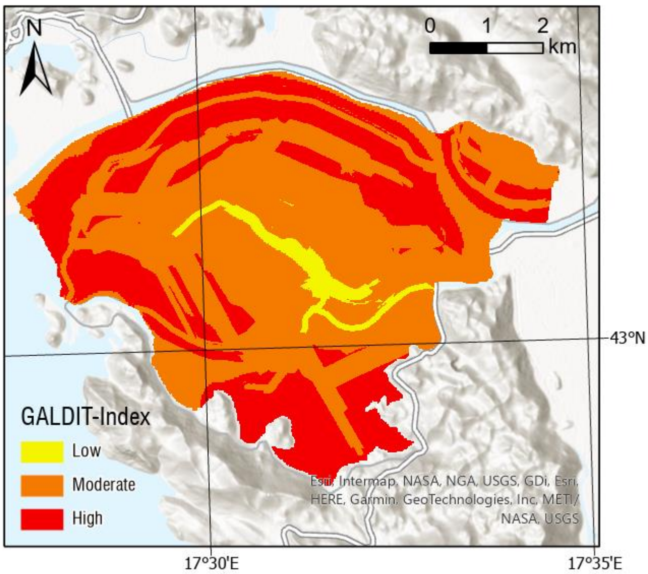


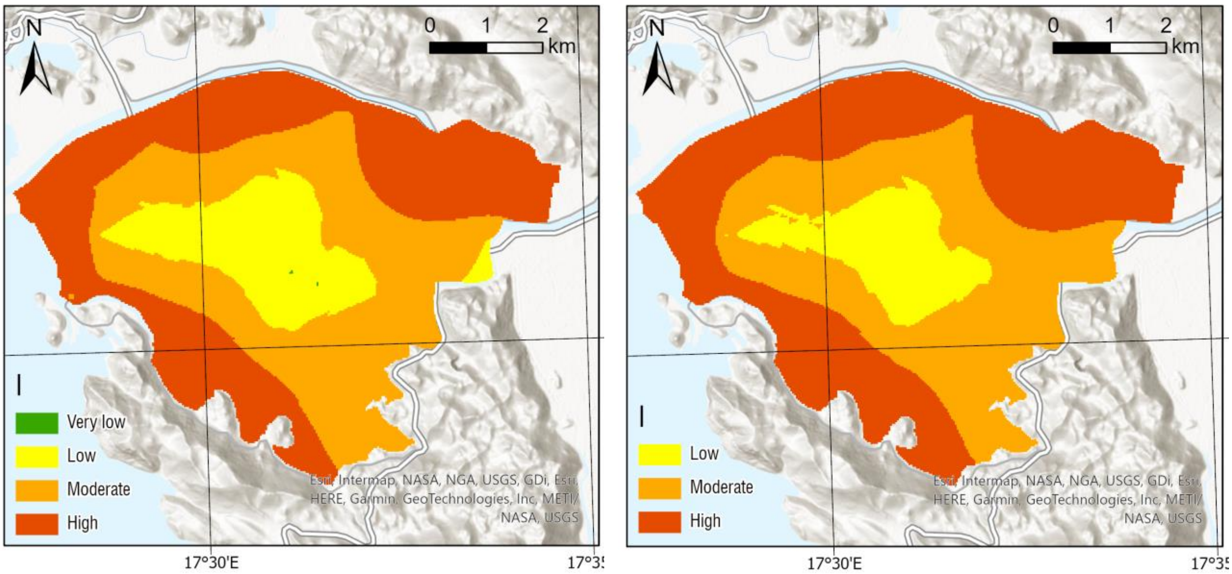
Figure 31 GALDIT index calculated using the weights and indicator ratings displayed in Table 9, and classified by the GALDIT-Index vulnerability categories from Table 3 for RCP 8.5 sea level rise scenario of 0.84 m.

Reduction in annual precipitation

Reduction in annual precipitation was assessed by the GALDIT Impact of existing status of seawater intrusion (I) indicator. In this work, a TDS water quality parameter was selected as GALDIT I indicator. In order to simulate the effects of precipitation reduction, two scenarios were determined:

- 10% increase in TDS and
- 30% increase in TDS.

In comparison with Figure 25b, an increase of moderate and high vulnerability area and decrease of very low vulnerability area is exhibited. In Figure 32b very low vulnerability area completely disappears and three higher vulnerability classes are seen.



(a) (b)

Figure 32 Impact of existing status of seawater intrusion (I) GALDIT indicator for lower river Neretva aquifer: result for 10% increase in TDS (a), result for 30% increase in TDS Table 2(b).

Modified GALDIT vulnerability index for two precipitation reduction scenarios is shown on Figure 33. It was determined as weighted average of the seven modified GALDIT vulnerability indices whose corresponding numerical ranking system is documented in Table 9.

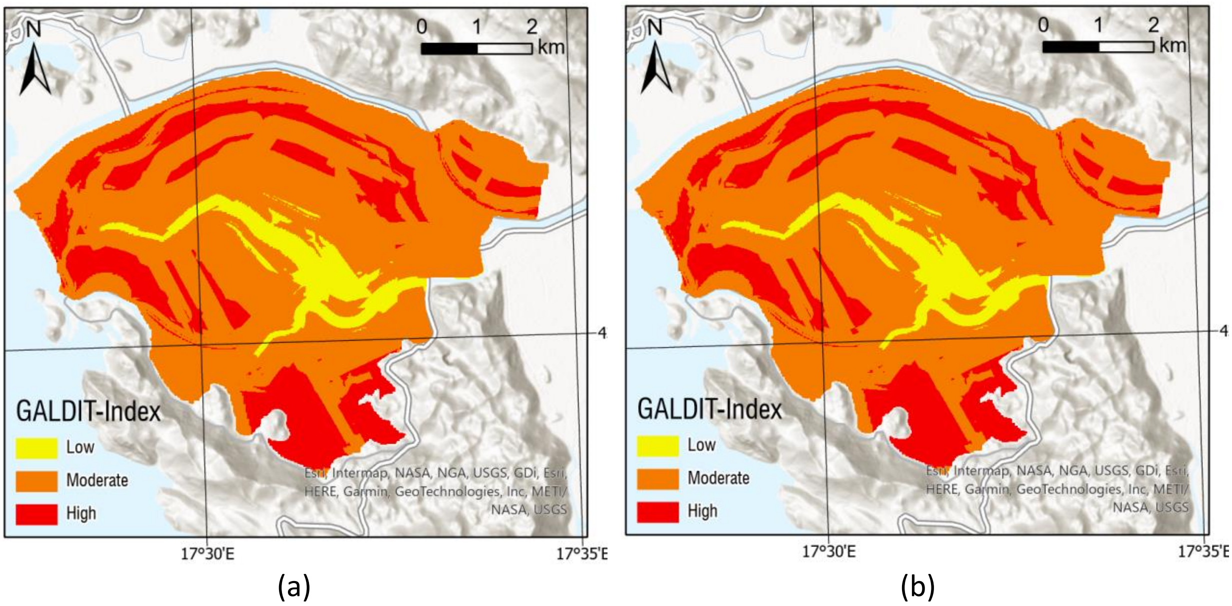


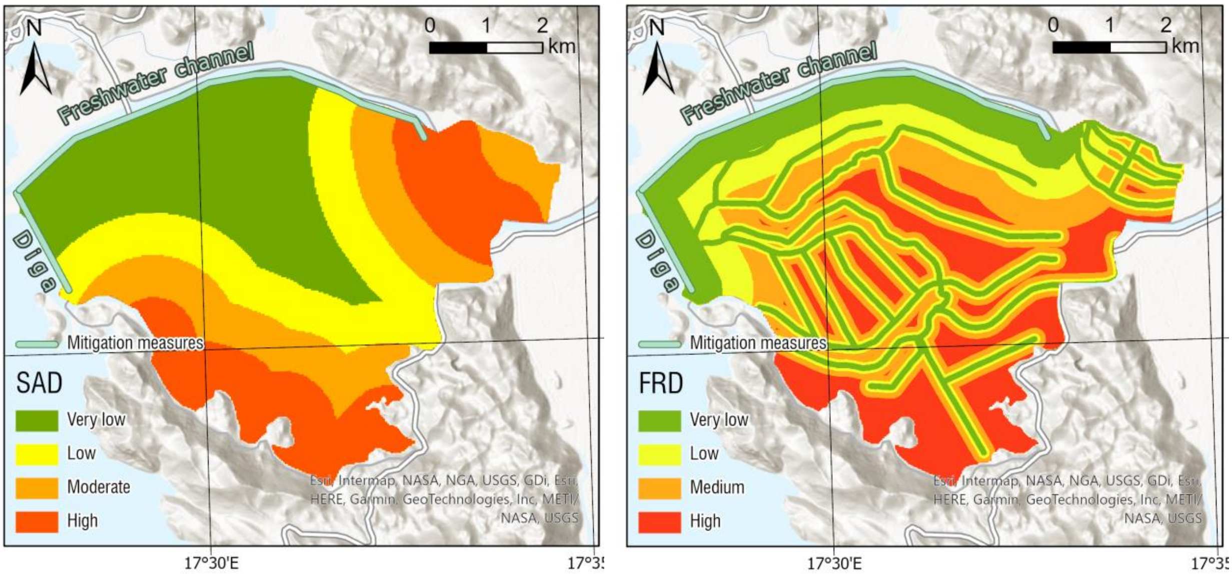
Figure 33 GALDIT index calculated using the weights and indicator ratings displayed in Table 9, and classified by the GALDIT-Index vulnerability categories from Table 3 for: 10% increase in TDS (a), 30% increase in TDS Table 2(b).

Mitigation measures

Suggested mitigation measures for saltwater intrusion in the lower river Neretva delta include:

- an eight km long channel filled with freshwater alongside the left bank of river Neretva, starting at Galicak hill at the river Neretva mouth and
- a freshwater injection at the 2 km long Diga embankment.

These mitigation measures would influence SAD and FRD indicators of the applied Modified GALDIT methodology. SAD source lines are basically removed in neighbourhood of the suggested mitigation measures (Figure 34a). The spatial influence of these measures on saltwater intrusion mitigation will be much larger than the ranges suggested for existing drainage/irrigation channels (Table 6). A more suitable ranges are the ones suggested for SAD (Table 5) but importance rating is used in reverse order, therefore, two intermediate FRD layers were created, one corresponding to the original FRD layer (Figure 24b), and one based on new channels but with ranges from Table 6. The final FRD indicator was determined as minimum cell value of the two intermediate layers (Figure 34b).



(a) (b)

Figure 34 Distance from saltwater (SAD) GALDIT indicator for lower river Neretva aquifer: classified 2D field by ranges and indicator ratings listed in modified numerical ranking system (Table 5) (a), distance from freshwater source (FRD) modified GALDIT indicator for lower river Neretva aquifer: classified 2D field by ranges and indicator ratings listed in modified numerical ranking system (Table 5 and Table 6Table 2) (b).

Three GALDIT index vulnerability maps including mitigation measures are presented on Figure 35 and 36a, b. Figure 35 represents the impact of mitigation measures on the existing situation, while the Figure 36a, b incorporates climate change scenarios. The more optimistic scenario can be seen of Figure 36a, while scenario with higher TDS increase and sea level rise is depicted on Figure 36b.

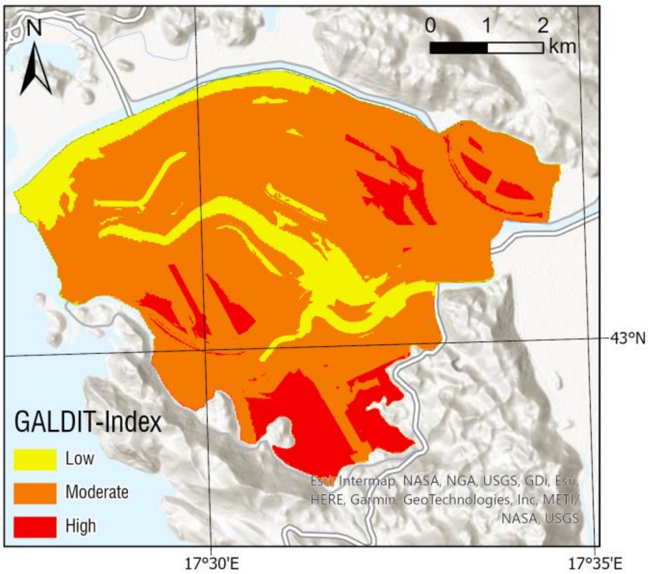


Figure 35 GALDIT index calculated using the weights and indicator ratings displayed in Table 9, and classified by the GALDIT-Index vulnerability categories from Table 3 for suggested mitigation measures.

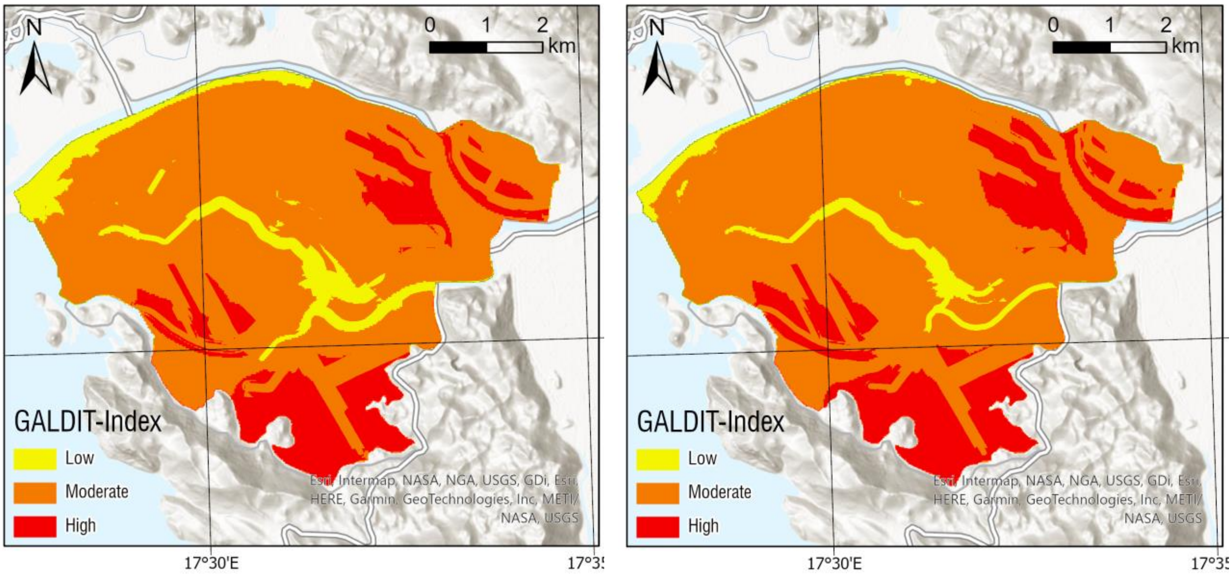


Figure 36 GALDIT index calculated using the weights and indicator ratings displayed in Table 9, and classified by the GALDIT-Index vulnerability categories from Table 3 for suggested mitigation measures and climate change scenarios: RCP 2.6 sea level rise of 0.43 m and TDS increase of 10% (a), RCP 8.5 sea level rise of 0.84 m and TDS increase of 30% (b).

Conclusion

Based on projected changes in ground air temperature, precipitation and mean sea level shown for global, European and Croatian area it is possible to conclude that changes are inevitable but values of changes vary based on projected scenarios (SSP2 – SSP5).

Based on EEA, ground air temperatures in Europe are projected to increase by 1.2 to 3.4° under the SSP1-2.6 scenario and by 4.1 to 8.5°C under the SSP5-8.5 scenario (by 2071-2100, compared to 1981–2010).

Based on DHMZ ground air temperatures in Croatia in the first period (2011-2040), are expected to rise up to 0.6 ° C for winter and up to 1 ° C for summer period. In the second period (2041-2070), the expected growth of the ground air temperature in Croatia is up to 2 ° C in the continental part and up to 1.6 ° C in the south for the winter period, and up to 2.4 ° C in the continental part of Croatia, and up to 3 ° C in the coastal zone for the summer period.

CCKP data show monthly mean temperature changes increasing by 1.36°C by the 2030s to more than 4°C by the 2090s.

EEA models project an increase in annual precipitation in large parts of central and northern Europe (of up to about 30 %) and a decrease in southern Europe (of up to 40 %) from 1971–2000 to 2071–2100. In summer, the precipitation decrease extends northwards. Values of projected change in annual precipitation for Croatian area based on Figure 10 is -5 to 5% and values od projected change in summer precipitation is -30 to -20%.

Based on DHMZ regional climate model, changes in precipitation in the near future (2011-2040) are very small and vary depending on the season. The largest change in precipitation can be expected in the Adriatic in the autumn with a decrease in precipitation with a maximum of approximately 45-50 mm. In the second period (2041-2070), change in precipitation in mountainous Croatia and in the coastal area will reach a value of 45 - 50 mm.

Based on EEA, global mean se level will rise by 0.28-0.55 m under a very low emissions scenario (SSP1-1.9) and 0.63-1.02 m under a very high emissions scenario (SSP5-8.5) by 2100, relative to the 1995-2014 average. Based on Figure 16 projected rise in sea level during 21st century in Croatian area will be 0.4 to 0.5 m.

Based on IPCC, global mean sea level will rise between 0.43 m (0.29–0.59 m, RCP2.6) and 0.84 m (0.61–1.10 m, RCP8.5) by 2100 relative to 1986–2005.

Based on [16] mean sea level in central and southern Adriatic will increase around 40 cm over the next hundred years, which is in line with IPCC and EEA forecasts.

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