Report on coastal vulnerability under climate change scenarios

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Summary

1 Foreword

This document has been produced in the framework of the INTERREG Italy – Croatia CHANGE WE CARE Project. CHANGE WE CARE fosters concerted and coordinated climate adaptation actions at transboundary level, tested in specific and representative pilot sites, exploring climate risks faced by coastal and transitional areas contributing to a better understanding of the impact of climate variability and change on water regimes, salt intrusion, tourism, biodiversity and agro-ecosystems affecting the cooperation area. The main goal of the Project is to deliver integrated, ecosystem-based and shared planning options for different problems related to climate change (CC), together with adaptation measures for vulnerable areas, to decision makers and coastal communities. Additional information and updates on the CHANGE WE CARE can be found at https://www.italy-croatia.eu/web/changewecare.

2 Abstract/Executive Summary

This activity benefits from the geomorphological assessment carried out in WP3 and of the hydrodynamic projections drawn in A4.1. This document highlights the most important elements of vulnerability to climate change for the different pilot sites: (1) Neretva River, (2) Jadro River (3) Nature Park Vransko Jezero (4) Banco di Mula di Muggia, (5) Po River Delta (Veneto Region) (6) Po River Delta (Emilia Romagna Region).

At the **Neretva River pilot site** great threat is represented by salt water intrusion, reduced inflow of fresh water and reduced river sediment input with consequent erosion of the deltaic deposits. One of the main difficulties in this case is a general lack of data and /or continuity of data collection required for the determination of baseline conditions (sediment flux, hydrological and meteorological data).

The pressures caused by climate change and human activities, which are the source of the **Jadro River delta** pilot site's vulnerability, will manifest themselves in a variety of environmental aspects. Water resource management is becoming more vulnerable as a result of increased water consumption from tourism and agriculture, as well as a decrease in precipitation. Vulnerability of agriculture is favoured by the increase in air temperature and heat waves, and the reduction of precipitation in the hotter part of the year in the future climate, and thus increased evapotranspiration. The vulnerability of infrastructure and buildings is due to rising urban development, which is associated with increased intensity of torrential waters on land and an expected sea level rise on the coast. Extreme events, such as heat waves, extreme rainfall events, and storm surges, have an impact on human health vulnerability, heat waves, in particular, will adversely affect tourism's vulnerability during the summer season. Finally, changes in the composition and number of plant and animal species reveal the vulnerability of terrestrial and marine ecosystems and biodiversity.

The impact of climate change on **Vransko Lake** is already evident at the present time. With the predicted global sea level rise, a new balance between the lake and the sea would be created, resulting in slightly higher lake water levels. However, the predicted increase in air temperature (and thus increased evapotranspiration in the basin and evaporation from the lake surface) and decrease in precipitation would have the effect of significantly reducing inflow into the lake system, resulting in a reduction in the water level in the lake and extending the periods when saline sea water penetrates the lake system.

An assessment of relative sea level rise scenarios in 2100 is proposed for the Adriatic sandy beaches of the **Po Delta** and the **Mula di Muggia** pilot sites, with an evaluation of the different components: sea level rise and land subsidence. The analysis was supplemented by estimations of net long-term sediment flows, with the goal of identifying erosional and depositional hot spots in general. The upper-shoreface sediment budget as well as the morpho-evolutive properties of the beaches / barrier islands were then developed to produce a short-term assessment of the Coastal Vulnerability Index applied to coastal homogenous tracts. Finally, different flooding maps with respect to long-term (2100) relative sea level rise are presented from scientific literature (Delta Po) or elaborated from the most recent Digital Terrain Model for the area (Mula Muggia).

Finally, the morpho-sedimentary data was used to create a Coastal Zoning map for the Mula Muggia pilot site, with the goal of outlining priorities and strategies to be addressed in the Adaptation/Management Plans (WP5).

3 Morphological evolution at the multi-decadal scale at pilot sites

The present Report, concerning the activity 4.2.1 “Morphological evolution at the multi-decadal scale”, has been drawn up with the contribution of all the partners (Figure 3-1).

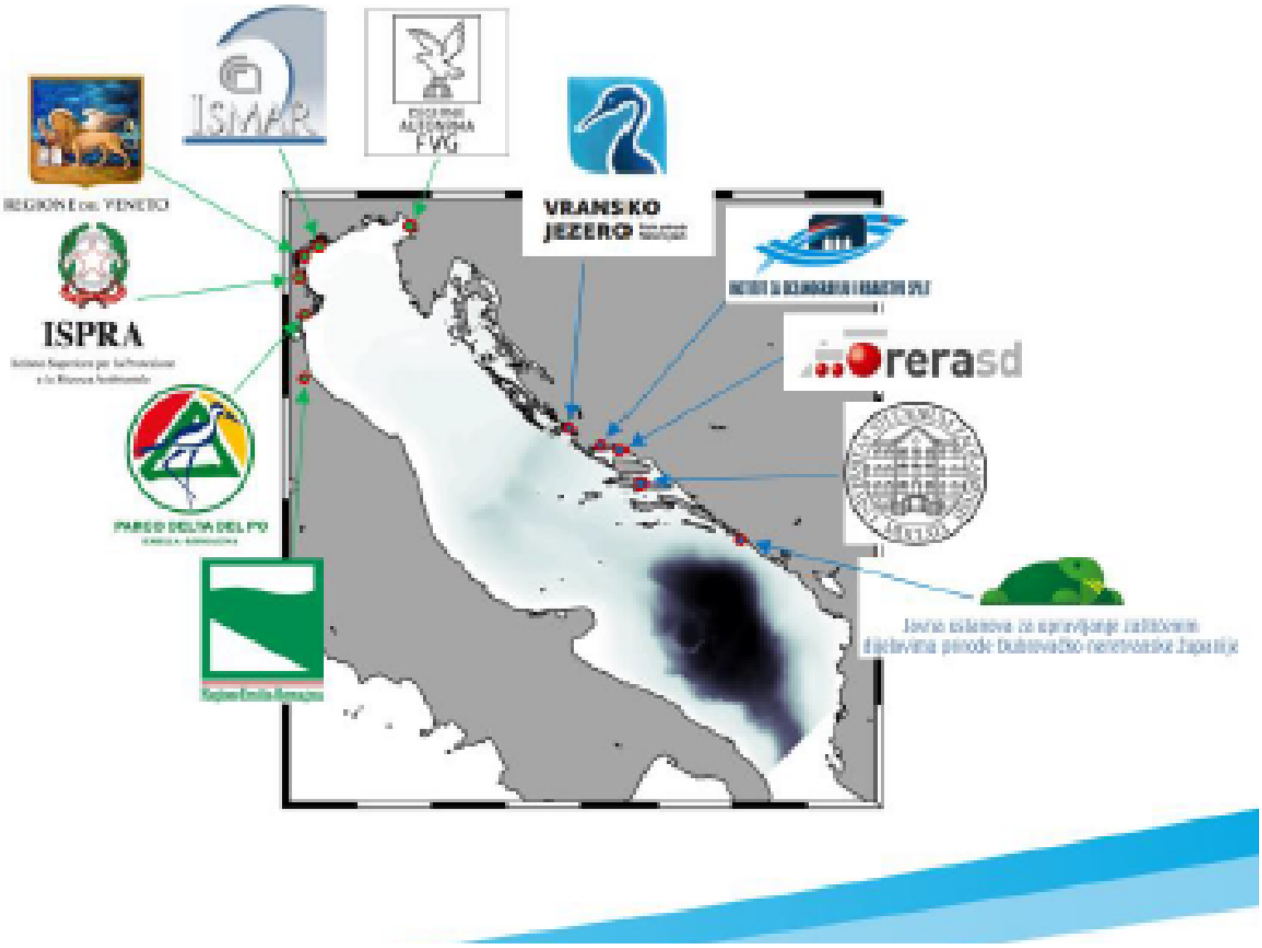

Figure 3-1 Partners involved in the Change We Care project

This deliverable provides information on the pilot areas (Figure 3-2).

1. Neretva River
2. Jadro River
3. Nature Park Vransko Jezero
4. Banco di Mula di Muggia
5. Po River Delta (Veneto Region)
6. Po River Delta (Emilia Romagna Region)

Figure 3-2 Location of the pilot sites of the project Change We Care

3.1 Neretva River site

3.1.1 General site description

Neretva River and its delta is the major and dominating geomorphological feature in the area. Delta area is composed of three geomorphological parts that are generally tectonically predisposed: Čapljina area in Bosnia and Herzegovina, Metković and Opuzen areas in Croatia (Figure 3-3). The Dinaric Karst bedrock has been incised by the paleo-Neretva River during the last glacial period, and Neretva Delta took current form during Holocene, when the Adriatic Sea rose to the present-day levels (Juračić, 1998).

Long term sediment flux

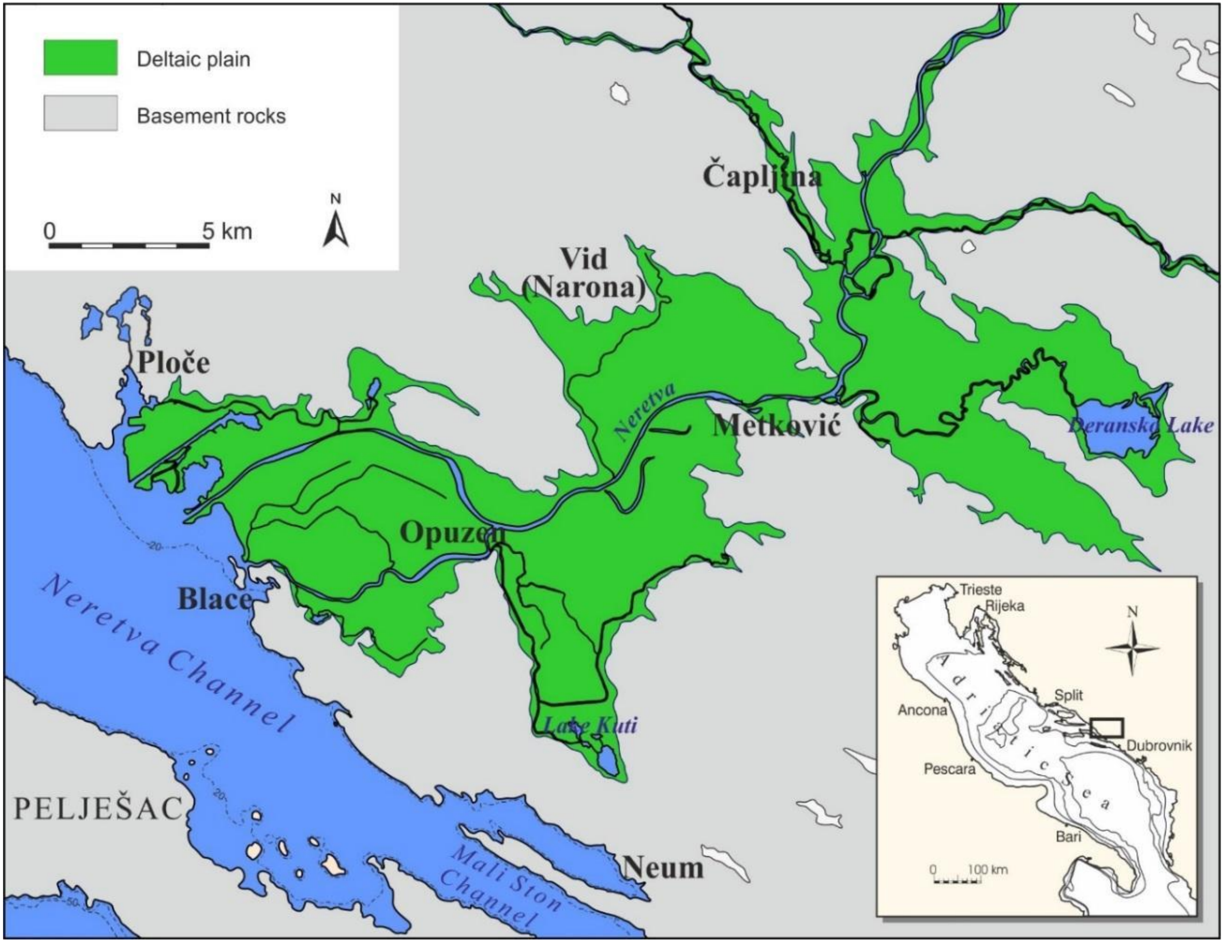

Figure 3-3 Neretva River Delta (deltaic plane) is a major geomorphological feature in the southern part of the Dinaric Karst that is built predominantly by the carbonate rocks (basement (bedrock) of the delta). Source: http://geol.pmf.hr

Mesozoic carbonate rocks that make up the karst bedrock and the wider perimeter of the delta were deposited on the former Adriatic carbonate platform (Vlahović et al., 2005) (Figure 3-4). Overlying Paleogene carbonates and clastics were deposited during the orogenesis of the Dinarides, and the Neretva Delta in general geotectonic subdivision is situated in the External Dinarides that are characterized predominantly by highly deformed succession of the carbonate and clastic rocks (Korbar, 2009). Karst bedrock is characterized by a dissected relief, numerous caves and sinkholes within the fractured carbonate rocks. The oldest rocks are the Upper Triassic dolomites that are overlayed by a zone of Jurassic carbonates, both outcropping along the NW-SE striking zone in the basement of the river mouth and along the coastal area. Cretaceous limestones and dolomites predominate in the area but there are also structurally constrained narrow and elongated NW-SE striking (Dinaric strike) zones of the Paleogene carbonates and clastics.

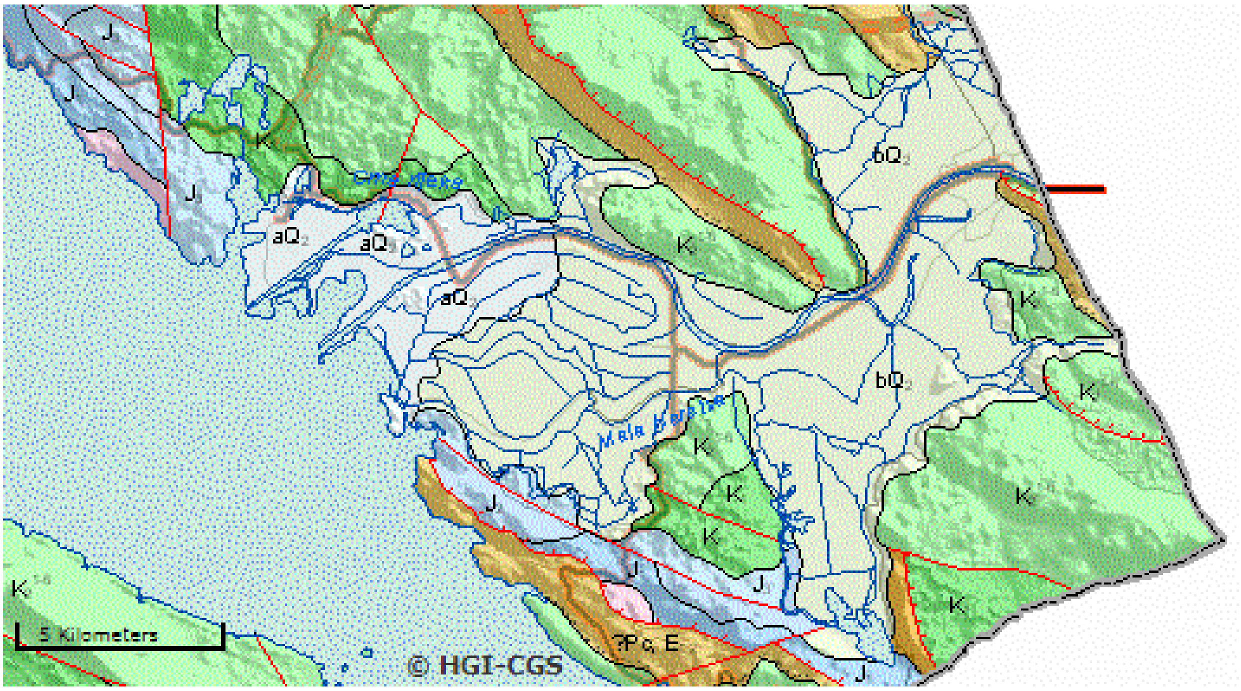

Figure 3-4 Crop of the Overview geological map of the Neretva delta area in Croatia. Grey - delta sediments (aQ_2 – alluvial, bQ_2 – palustrine), Orange – Cenozoic carbonates and some clastic rocks (Pc, E), Green – Cretaceous carbonates (K), Blue – Jurassic carbonates (J), Purple – Triassic carbonates (T). Source: HGI-CGS: http://webgis.hgi-cgs.hr/gk300/default.aspx

There are three general morphological units of Neretva Delta area: the karst hinterland, lowland area of the delta and the coastal strip (Nature Park Neretva Delta, 2007). Within the regional geomorphological and geological framework, the karst basement of the delta can be simply defined as a flattened bedrock area along the lower river channel covered by superficial Quaternary loose sediments deposited by the river during Quaternary that resulted with the present-day shape of the delta (Juračić, 1998). Southwest of Metković the topmost Quaternary sediments are characterized mostly by palustrine sediments (organic rich swamp mud), while west of Opuzen and down to the river mouth are represented by delta sediments: sand, gravel and sand - clay material. It can be assumed that the beginning of the creation of the present-day delta fall in the age of sea level rise, roughly before 8000-6000 years (Juračić, 1998).

Neretva originates southeast of Zelengora at an altitude of 1095 m, mainly flows through Bosnia and Herzegovina, and flows into the Adriatic Sea south of Ploče. It is about 218 km long, out of which in Croatia ~22 km. In the upper and middle part of the flow Neretva river is representing a typical mountain passing narrow valleys with steep slopes. Downstream of Počitelj, Neretva leaves canyon and flows through the valley of the meander-nut (Ljubenko and Vranješ, 2012). The stream base forms a main stream which is navigable to Metković and Mala Neretva, which is separated from the main flow on the left from Opuzen. Watercourses of the left hinterland of Neretva river are Mislina and Jezerača with a source in the lake Kuti. Both after the composition passes in Prunjak that flows into Mala Neretva near Opuzen. Watercourses are right waterside Glibuša, Norin, Nut, Desanka and Crna rivers. Desne are a pit which is spring zone of the upper horizons (Vrgorac field and Rastoka). A series of springs is located on the contact of the valley with karst, most notably the Modro oko. The whole basin is collected in the central part of the valley in lake Desne, and from there it flows into the Neretva river through Desanka and the port of Ploče (Lake Vranjak) through the Black River. A new port of Ploče channel reduced the flow of the Black River, which is now much less refreshing the lake Birina, beside which flows into the sea. The regulation works in the course of the Neretva towards the end of 20th century and contemporary land reclamation significantly changed the number and spatial distribution of the lakes. Lakes area in the Croatian part of the delta before reclamation totaled 1,404 ha, followed by reclamation it decreased to 635 ha. The most important lakes before reclamation were: Modrič, Glogačko lake, Životina, Dragače, Timenica and Palinić. Today there are still Desne lake, Lake Vlaška, Parila and Kuti. Modro oko and source of the Norin in Prud are most important springs capped for water supply of the village. Outside the alluvial plains are Baćina lakes. Baćina lakes are cryptodepression, consisting of five connected lakes: Lake Plitko, Podgora, Očuša, Sladinca, Crniševa and separate lake Vrbnika. The largest is Lake Očuša (55.4 ha) and the maximum depth was measured in Crniševo (31 m). Despite the sea and permeable karst terrain lakes are filled with fresh water (County Development Strategy 2016-2020).

River has many tributaries that flow into the main water stream directly or indirectly underground karst flows (Margeta and Fistanić, 2000). Large amounts of water come in the delta area trough sources which are located along the perimeter of the alluvial plain, which are especially generous in the rainy part of the year. Those additional quantities of water from areas outside orographic basin (Juračić, 1998) come through karst underground.

Most of the rainfall occurs in the winter period (November), while the least rainfall is in the summer, so the middle summers are sometimes with no precipitation, and the annual evaporation is 500-900 mm. The mean annual flow of the river is 269 m3 / s, the minimum is 44 m3 / s (probability 0.05), and the largest 2,179 m3 / s (probability 0.01). Runoff coefficient is about 0.871. The flow is measured at 21 measuring station for more than 30 years.

Water quality is mostly satisfactory, except in parts of the river with large settlements and downstream from them (Margeta and Fistanić, 2000). In the dry summer period, due to the reduced flow of fresh water from the basin, intrusion of the sea water into the interior of the basin increases through the riverbed and underground trough fracture karst system and through alluvial valley (Ljubenko and Vranješ, 2012). Moreover, the entire valley main inflow of salt water (sea) occurs in the deep layers of the alluvium

(Vranješ et al., 2013). In this way, water in surface watercourses becomes very saline, particularly in the bed of the Neretva, as well as ground water. In summer sea water wedge penetrates through the Neretva river bed upstream up to Gabela. Under the influence of freshwater wedge is pushed downstream until it is fully ejected out of the river bed (Ljubenko and Vranjes, 2012).

The process of salinization all over the valley at the present time is quite pronounced, and the water regime of the river is completely changed compared to the natural state, due to the construction of the hydropower system in Bosnia and Herzegovina. So far in the Neretva river basin there is nine hydroelectric power plants constructed, and two more are planned. In the basin of the Trebišnjica there are seven already built, with three planned in the system called “The Upper horizons”. Also, five reservoirs and lakes are already built, and five more in the expansion plan.

Changes in the basin that will occur due to further construction of hydropower systems are cross-border issue of Croatia and Bosnia and Herzegovina. The consequences of the activities will be felt in the Neretva delta, Mali Ston and the Župa Bay, and water sources in the Dubrovnik coast (Vranješ et al., 2013). The consequences of changes in the water regime are most noticeable in the area of Lower Neretva. A direct consequence of reduced water regime is salinization. Also, amount of river sediment deposit coming from the basin is reduced, which is causing elution of Neretva riverbed in the area of Lower Neretva during the flood waters, especially near the mouth.

The Neretva Delta is a valley in the south of the Croatian Adriatic coast, formed at its mouth by the Neretva River itself. The Delta covers an area of 12,000 acres. The Neretva Delta from Metković to the estuary from the north and northeast is bounded by the branches of the Dinaric mountains, and from the south by the Podgradina-Slivno hills.

Figure 3-5 Orthophoto image of the Neretva River mouth (source DGU: https://geoportal.dgu.hr/)

The area has Mediterranean climate with mild, rainy winters and hot, dry summers. Here are some basic climate characteristics according to data of the Meteorological and Hydrological Service of Croatia. The air temperature has an average value of 14-15 °C. The coldest is December – February period with average temperature of ~7°C, although temperatures can go down to -5°C or even below. The temperatures are highest in July (average ~25°C) and August and can go over 40°C. Average annual precipitation ranges from 1,250-1,500 mm. December is the rainiest month while July is the driest one with less than 200 mm. Humidity is highest in September, December and January (average 72%) and the lowest in July and August (average 54%).

Neretva River is the dominant watercourse of the area. Its main characteristics in this final section are: average annual water level of 91±13 cm (range 65-124 cm); average annual water flow of 269 m^3/s (range 44– 2,179 m^3/s); average annual water temperature near Metković being 11.9 °C (range 0 -26 °C). River has a high water level in winter, while during summer there is a lack of water. This is partly due to several hydropower plants upstream in Bosnia and Herzegovina, which hold the most of Neretva waters with dams. In such situations when Neretva has a very small flow downstream of the dams, marine waters enter the river, spreading its influence upstream all the way to Metković (border with Bosnia and Herzegovina). Hydromorphic soils prevail in Neretva Delta. Narrow zones along watercourses are covered with alluvial soils (fluvisol). Amphigley soils are represented in wider area, receiving water from rainfall as well as from underground water. Surrounding carbonate hills are covered mostly with calcicambisol (‘brown’ soil on carbonates) and mould (‘black’ soil).

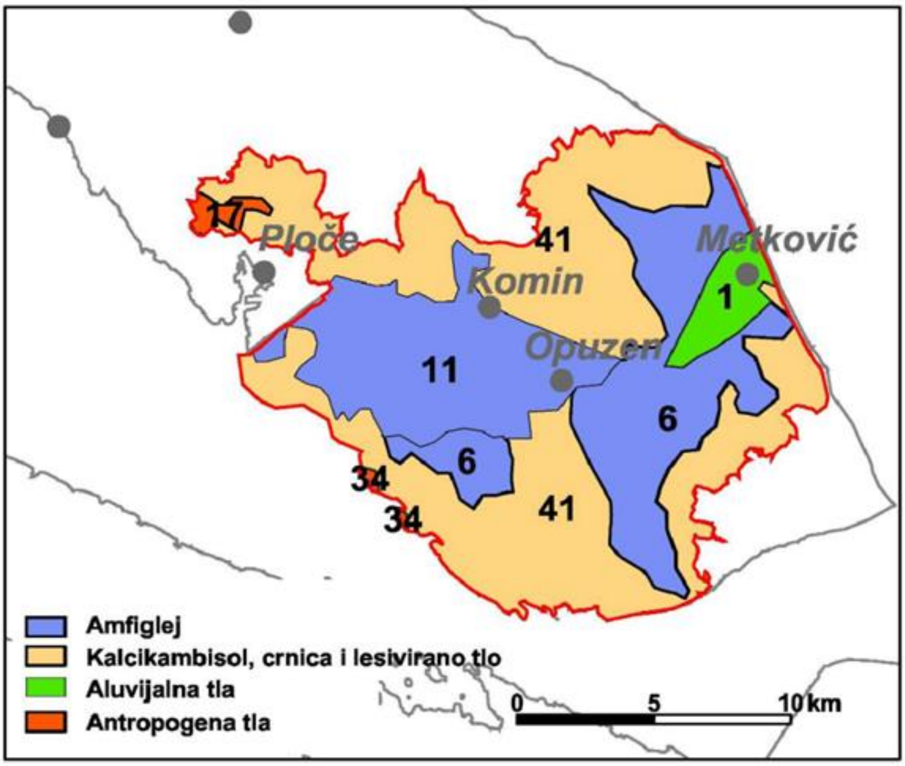

Figure 3-6 Soil map of Neretva Delta River (Source: Soil map of Republic of Croatia, Martinović, 2000)

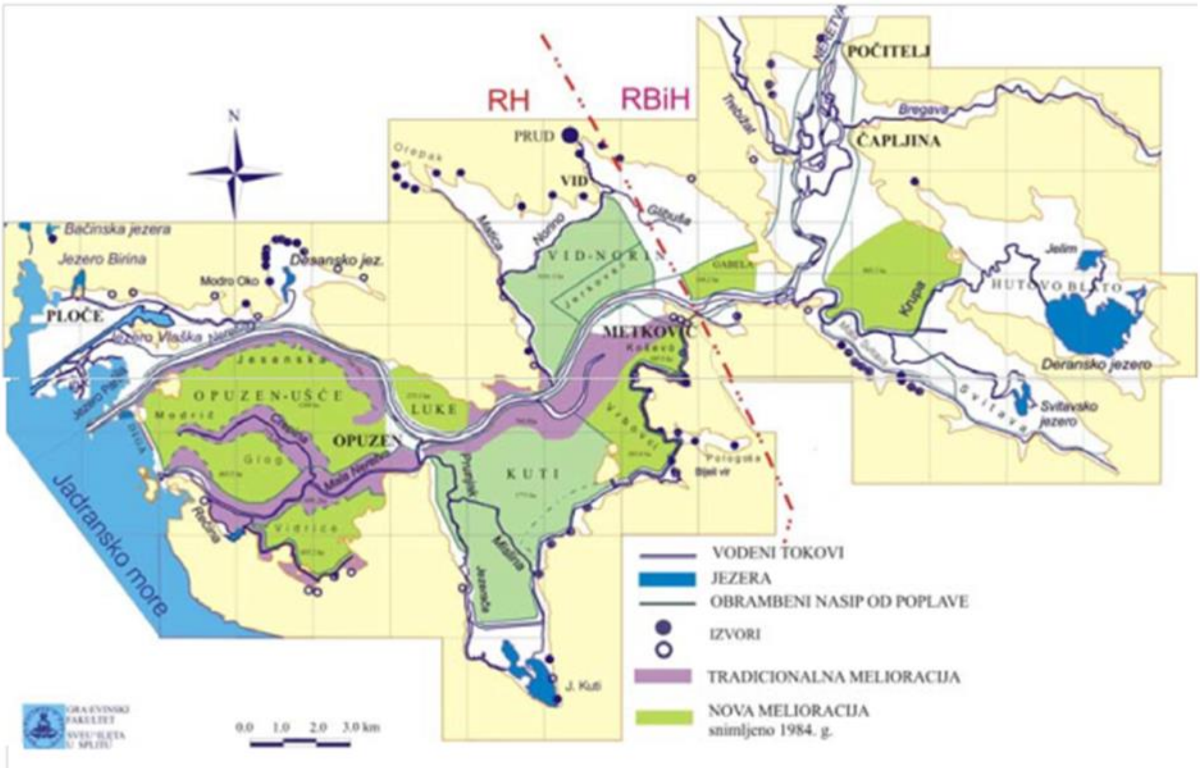

Figure 3-7 Hydrological status in Lower part of Neretva today (Source: Vranješ et al., 2013)

Neretva River Delta is designated as internationally important wetland under the Convention on Wetlands (Ramsar, 1971). It contains the largest complex of wetlands in Croatian littoral with well-developed water-fringe vegetation (the largest reedbeds in the country that cover more than 3,000 ha, sedge communities, rush), floating and submerge vegetation around Neretva and its tributaries.

Also, it is a Natura 2000 site HR1000031 Delta Neretva (SPA), HR5000031 (SCI).

In the Neretva River Delta, there are protected areas of nature according to Croatian Law of nature protection:

-5 ornithological special reserves: Prud, Pod Gredom, Orepak, Modro oko and jezero Desne, Kuti

-ichthyological-ornithological special reserve Ušće Neretve

-significant landscape Predolac–Šibenica.

Neretva Delta is the most valuable wetland on eastern Adriatic coast and one of only few wetlands remained in Mediterranean region of Europe. The mouth of the river Neretva is characterized by wide lagoons, sandflats and saltmarshes. Though a large area of the wetland habitat has been transformed into agricultural lands, due to the branching network of channels, these areas are still important habitats for aquatic birds and a very important ichthyological area. Reclaimed land is covered by agricultural landscape with many irrigation channels. The Neretva Delta has many lagoons, shallow sandy bays, low sandy shores, sand flats, salt beaches, etc. The delta, lagoons and brackish waters are an exceptionally important habitat which creates room for the intensive growth of fry, which later spend their life cycle in the sea or fresh water. Furthermore, these areas are important for the migration of anadromous and catadromous fish species. Neretva Delta is important for breeding, migration and wintering of almost 200 regularly occurring bird species.

Salt water intrusion in Neretva River Delta, reduced inflow of fresh water and reduced sediment deposit represent great threat for delta. Due to this there is a change in the environment conditions in the coastal sea, and the fresh water ecosystems which results in reduction of wetlands. All of this directly affects the biodiversity of the area, target species and the habitat Natura 2000.

Furthermore, as a consequence of human activity in the area, there is the distribution of contaminants in water and soil. All previously listed has a direct impact on reducing the quality of life of local communities, and loss of extremely valuable areas of biodiversity.

Neretva River Delta is an area with a lot of different influences, so there are numerous activities that have or could have negative impact on the natural values site Delta Neretve, such as: planned tourist zone in Natura 2000, kite surfing activities close to Ichthyological - ornithological special reserve Ušće Neretve – illegal land reclamation, Illegal hunting etc..

The future of this area should be based on balancing the need for further development and the need to protect natural resources. Within the Project it’s important to define guidelines to effectively oppose salt water intrusion without obstructing fish migration, as well as guidelines for preservation of wetland area in Neretva River Delta, all respecting the needs of the development of the local communities.

The Neretva Delta area is very densely populated with about 35,600 inhabitants (2011), with the majority of the population living in the cities of Metković (16,788), Ploče (10,135) and Opuzen (3,254) situated in the westernmost part of the Dubrovnik-Neretva County (Croatia).

People are present in Neretva Delta for thousands of years, turning wetland into arable land and establishing transportation routes towards the hinterland. Locals use the delta area mainly for agricultural purposes and for production, but also for activities such as hunting, fishing and aquaculture. With the beginning of the first land reclamation and changes in the course of the Neretva river, especially contemporary interventions in the last 50 years, the man began to change significantly the natural characteristics of the delta and thus dictate the economic orientation and the location and form of settlement. Until then local community lived on fisheries, hunting and agriculture which depended on traditional way of land reclamation called “jendečenje”. That is traditional way of creating land parcels in the marsh (digging channels and putting excavated soil aside, thus making small land plots). These traditional channels are called “jendeci” and form unique, specific landscape in Europe. Land ownership is one of the most significant issues related to land use and management in Neretva Delta. Situation with property rights in the area is very complex and the status of the most of agricultural land is not clear (state vs. private ownership). A part of the State-owned agricultural land is being leased to local people.

The population is also increasingly turning to tourism. In recent years, the tourist offer has been supplemented by activities such as photo safari trips, kitesurfing, windsurfing, cycling, agritourism and gastronomy. The main visual identity of the area is the reclaimed agricultural landscape with many irrigation channels.

It is important to highlight the specific geographic location of the Neretva delta which created precondition for forming important traffic intersections of main roads, rail and maritime transport. The important part of local economy in area is cargo seaport in Ploče, second in Croatia by the amount of transhipment, a multi-purpose port for transhipment of almost all kinds of commodities represented in international maritime transport. An integral part of the port of Ploče is Metković port which is located 20 km upstream on the river Neretva.

The most prominent factors in the past that adversely affected ecological character of Neretva Delta were connected to water management, including land reclamation activities with the purpose of turning wetland into agricultural land. Today the largest threats are also connected to issues of water management and agriculture sectors. As the consequence of water regulation activities in surrounding area of Croatia in Bosnia and Herzegovina, there is an obvious trend of decrease of water level and quantity in Neretva Delta that adversely affect not only wetland habitats and biological diversity of Delta but also agriculture. The less water in Neretva and its tributaries in Delta, the stronger influence of the sea and salinization of water and soil can be expected. There are different water management plans and projects currently going on in Neretva Delta. They deal with solving the problem of salinization; irrigation of agricultural land; flood control, treatment of sewage water of the town Metković and other activities. There are even plans for further meliorations of remained wetland areas. Other problems and threats to ecological character of the Neretva Delta include: expansion and intensification of agriculture; excessive use of pesticides and fertilizers; fragmentation of wetland habitats; spreading of urban zones on account of wetland; water pollution with non-purified urban and industrial waters; unsolved land property rights; illegal taking of state owned agricultural land, including marshes; non-regulated recreational and touristic activities, especially on the river mouth, illegal hunting and fishing; frequent fires in reedbeds.

In the surrounding area:

In the surrounding area especially problematic are issues related to transboundary water management and numerous water regulations in catchment area of the Neretva and neighboring Trebišnjica River in Bosnia and Herzegovina. Watersheds of these two rivers are connected through karst underground. Re-direction of waters from so called Upper horizons (“Gornji horizonti”) of Trebišnjica River into the area of Lower horizons (“Donji horizonti”) with three existing hydropower plants results in loss of water in lower Neretva area, lower summer water level, drying out of water springs and strengthening of influence of the sea. There are plans to even increase these activities and to take the most of available water for additional use of hydropower plants in eastern Herzegovina.

3.1.2 Assessment of sea level rise scenarios in the considered coastal and transitional areas

Off the Neretva River delta, the mean annual temperature (Figure 3-8) has values rising from 18.5-19.0 [1]C at the beginning of the AdriSC simulation to around 19.5-20.0 oC at the end of the AdriSC simulation. The positive trends are strong in all seasons (Figure 3-9). Sea surface salinity has strong interannual variability, ranging from 38.2 to 38.7, with lowest values in summer (Figure 3-10, Figure 3-11). Sea level constantly rose in the considered period but having strong interannual variability (Figure 3-12), yet with quite strong interannual variability and being the highest in autumn and then I summer (Figure 3-13).

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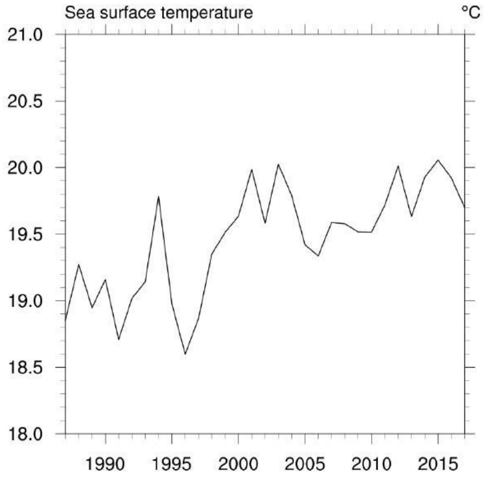


Figure 3-8 Annual sea surface temperature at the Neretva River site as simulated by the AdriSC modelling suite (1987-2017).

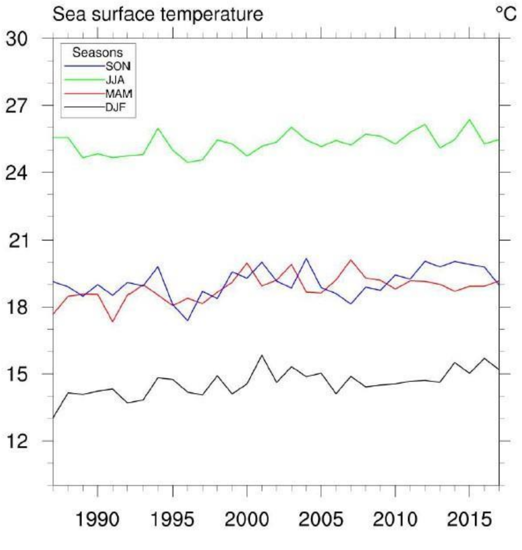


Figure 3-9 Seasonal sea surface temperature at the Neretva River site as simulated by the AdriSC modelling suite (1987-2017).

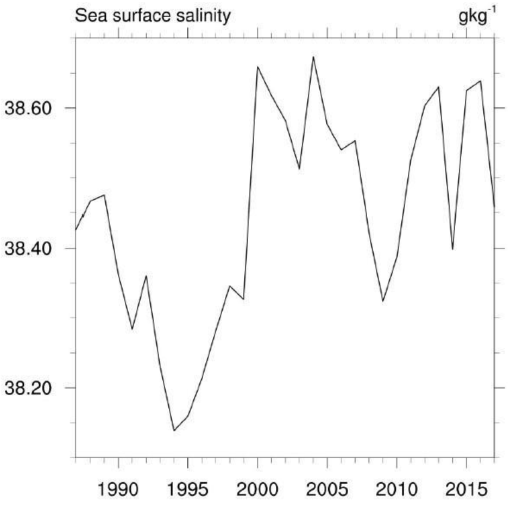


Figure 3-10 Annual surface salinity at the Neretva River site as simulated by the AdriSC modelling suite (1987-2017).

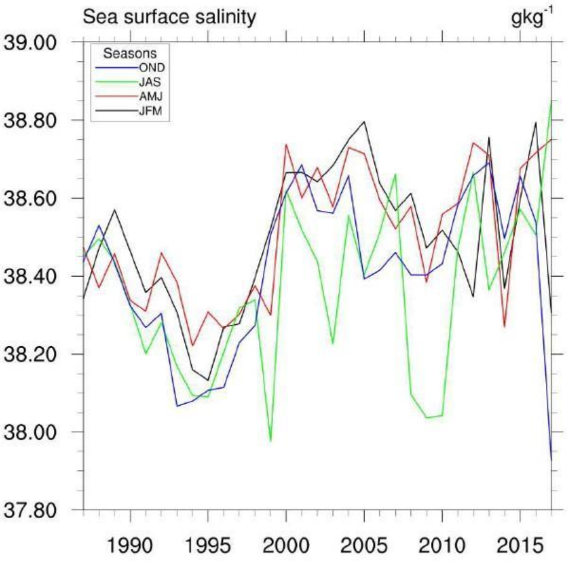


Figure 3-11 Seasonal surface salinity at the Neretva River site as simulated by the AdriSC modelling suite (1987-2017).

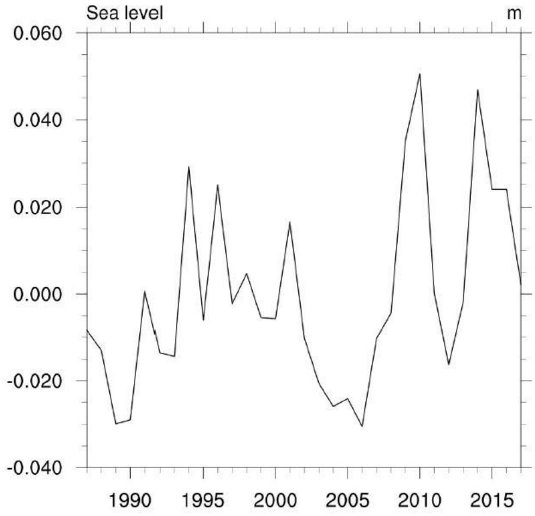


Figure 3-12 Annual sea surface height at the Neretva River site as simulated by the AdriSC modelling suite (1987-2017).

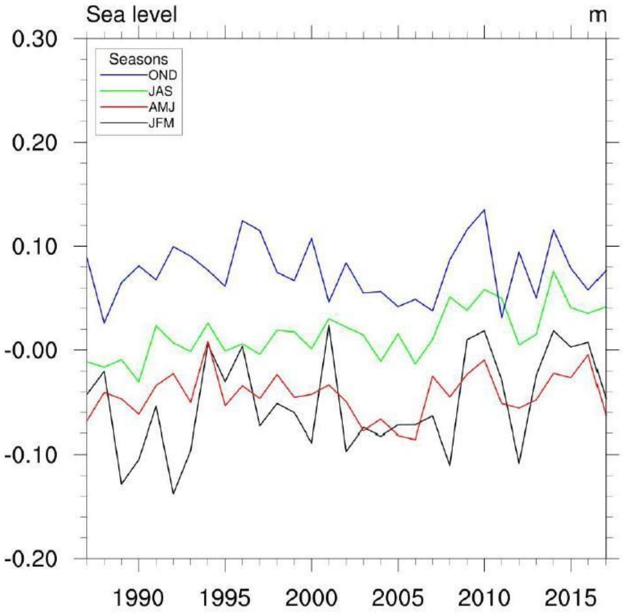


Figure 3-13 Seasonal sea surface height at the Neretva River site as simulated by the AdriSC modelling suite (1987-2017).

3.1.3 Long-term sediment fluxes and identification of erosional and depositional hot spots

There is a correlation between water discharge and drainage basin lithology. Due to the nivo-pluvial regime with an impermeable upper drainage basin, together with high relief ration, climatic variation, and scarce vegetation, Neretva River is considered to have a high sediment flux. Additional sediment load is due to the flysch bedrock in its lower drainage basin. As an allogenic karstic river, Neretva discharges a large quantity of particulate sediment into the Adriatic compared to other Croatian rivers. The valley in which the deltaic plain is situated was incised in the karstic relief during the lower sea-level stand. The valley was submerged during the last sea-level rise and an estuary was formed. Strong natural sediment supply and the negligible tidal and wave activity resulted in rapid delta growth. Sediment analyses of the 100 m long sediment core from the Mali Ston Channel showed that terrigenous and carbonaceous sedimentation alternated during the Pleistocene and Holocene delta growth, indicating occasional periods of significant terrigenous flux interchanged with normal carbonate sedimentation characteristic for the eastern Adriatic Sea (Felja et al., 2016).

However, sediment input is nowadays substantially reduced due to the sediment trapping in reservoirs behind large dams. In totally, 9 dams (including ones on the Neretva River tributaries) trap most of the particulate material in the part of the drainage basin upstream of Mostar, approximately 70 km away from the river mouth. The most complex dam is one on the Trebišnjica River which has a negative impact on the deltaic plain and the Neretva River: it significantly reduces water and sediment discharge, increasing thus riverbed erosion (Bonacci and Jelin, 1998). Additionally, uncontrolled sand and gravel mining additionally reduced sediment discharge. It is estimated that total excavated quantities of sediment are > 20 times higher than ones of natural replacement of the sediment material. Most of the sediment brought by the Neretva River deposits in the main river channel. Sediment cores presented by Vranješ et al. (2007) showed that muddy sediments prevail in the topmost horizons of the sediment sequences and it was correlated with the period after river damming and/or to the sea level rise. According to Jurina et al. (2015) Neretva River plume discharges its load over a wide area of the Neretva Channel, resulting in a relatively uniform depositional rate. Specific sediment transport is estimated to be 1093 t km2/y (EUROSION, 2004). Long-term runoff decreases and retention of the sediment material in the upper part of the drainage basin led to the reduction of sediment fluxes, especially during the last 70 years. As a consequence, delta is no longer expanding or even decreases.

3.1.4 Short term and long term vulnerability

One of important characteristics of each water resource system is the ability of its satisfactorily operation under a wide range of natural hydrologic conditions and demands. Understanding of the system functioning and knowledge about its current ecological state provides a rational basis for predicting system behaviour under new conditions such as extreme weather episodes (e.g. droughts), increasing anthropogenic demands and climate changes. In order to describe this behaviour during additional demands, Hashimoto (1982) proposed a comprehensive analysis of the system performance. System performance can be described from three aspects: how often the system fails (reliability), what is the recovery rate of the system from unsatisfactory state (resilience) and how severe the damage caused by a system failure may be (vulnerability). Thus, the analysis based on these three criteria: reliability, resilience, and vulnerability (RRV analysis). This analysis focuses on system failure, defined as any output value reaching the predefined failure threshold. Measurement of these three criteria should be used in water resources management and operating policies.

Due to the anthropogenic causes and climate changes, functioning of water resource systems are becoming increasingly complex with increasing number of possible risks. In order to manage these risks determination of system baseline conditions is needed, however, baseline performance analysis for most of water systems is not done. Furthermore, the RRV concept requires determination of failure thresholds as well as the criterion for satisfactory state. In case of the Neretva River Delta baseline condition does not exist. Overall, collected data compiled within this activity gave an insight into overall picture of sediment and water fluxes within the Neretva River Delta, however, quantification of both fluxes is still highly missing. **One of main difficulties in case of the Neretva River in whole is a general lack of data and the continuity of data collection required for baseline condition determination** (sediment flux, hydrological and meteorological data etc.). Compiled and here presented data have shown that the Neretva River Delta is a rather complex area, with sediment and water supply from drainage basin of mixed lithology. Its water discharge is considerably influenced by its karstic relief. Due to this complexity and the involvement of karstic groundwater discharge within, estimation and calculation of natural water discharge within the Neretva River Delta may vary (probably by several magnitude of order as in case of other Croatian coastal rivers). Despite the general data gaps, reconstruction of the water flux data is recommended in the future, especially for adaptation measures to be delivered within this project.

As far as the sediment flux within the Neretva River Delta is concerned, data were not collected so far and only a rough estimation is given in this report. In order to establish baseline conditions, satisfactory state and failure threshold for RRV analysis, monitoring of sediment flux needs to be established in the future as well. As described throughout the report, independent research results have shown that the topmost sediment cover within the Neretva River Delta and along the Neretva Channel where the sediment from the river plume is deposited contains generally fine-grained particles, compared to coarse-grained material deposited below (and before dam construction). This sediment fining clearly indicates considerable reduction of sediment input. As a consequence, erosion of the deltaic deposits has been detected. Due to the unknown quantities of natural sediment deposition rates within the deltaic plain, a careful reconstruction and estimation of sediment flux need to be established for period without measurements, in order to perform RRV analysis.

Together with dam construction in its upper part, intensive agriculture in deltaic part is the main recognized anthropogenic cause of water and sediment flux reduction, resulting in changes of sedimentological characteristics of deposited sediment material. As a consequence, delta erosion and seawater intrusion frequently occur. These processes are recognized as the main risks posed within the Neretva River Delta for both, protected areas and agricultural land. It is expected that climate change with recognized warming trend will further cause a decrease in water and sediment discharge. This reduction may further induce changes in physical and chemical conditions within the Delta and they may be a trigger of harmful substances remobilization, causing thus their release within the deltaic system. This domino effect may threat the human population as well, largely depend on food production within the Delta.

Thus, from the current point of view, quantities of both water and sediment supplied by the Neretva River need to be increased to reduce posed threats and/or annul their negative effects.

3.1.5 References

Bonacci, O., Jelin, J. (1998): Identification of a karst hydrological system in the Dinaric karst (Yugoslavia). Hydrological Sciences Journal 33/5, 483-497.

Development strategy of the Dubrovnik Neretva County for the 2016-2020 period. The Regional Development Agency of the Dubrovnik-Neretva County DUNEA

EUROSION (2004): Living with coastal erosion in Europe: sediment and space for sustainability. Part II Maps and statistics. DG Environment EC, 25 pp.

Felja, I., Romić, M., Romić, D., Bakić, H., Pikelj, K., Juračić, M. (2016): Application of empirical model to predict background metal concentration in mixed carbonate-alumosilicate sediment (Adriatic Sea, Croatia). Marine Pollution Bulletin 106(1-2), 190-199.

Hashimoto, T. (1982): Reliability, Resiliency, and Vulnerability Criteria For Water Resource System Performance Evaluation. Water Resources Research, 18/ 1, 14-20.

Institute of oceanography and fisheries, Adriatic Sea and Coast (AdriSC) modelling, Split

Juračić, M. (1998): On the origin and changes of the Neretva River delta), Časopis za književnost i znanost, Nova serija (0353-8559) 9 (1998), 4; 228-232, Dubrovnik

Jurina, I., Ivanić, M., Vdović, N., Troskot-Čorbić, T., Lojenc, S., Mikac, N., Sondi, I. (2015): Deposition of trace metals in sediments of the deltaic plain and adjacent coastal area (the Neretva River, Adriatic Sea). Journal of Geochemical Exploration 157, 120–131.

Korbar, T. (2009): Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Palaeogene carbonates. Earth-Science Reviews, 96, p. 296–312.

Ljubenkov I. and Vranješ, M. (2012): Numerical model of stratified flow – case study of the Neretva riverbed salination (2004), Građevinar 64 (2012) 2

Margeta, J. and Fistanić, I. (2000): System management and monitoring at the Neretva river basin, Građevinar, Vol. 52 No. 06, 2000.

Vlahović, I., Tišljar, J., Velić, I. & Matičec, D. (2005): Evolution of the Adriatic Carbonate Platform: paleogeography, main events and depositional dynamics − Palaeogeography, Palaeoclimatology, Palaeoecology, 220, 333–360.

VRANJEŠ, M., VIDOŠ, D, GLAVAŠ, B (2007): Status of sediments in the lower Neretva River. In: GEREŠ, D (ED): 4. Hrvatska konferncija o vodama, Hrvatske vode i Europska unija – izazovi i mogućnosti, Zagreb, Hrvatske vode, 337-344.

3.2 Jadro River site

3.2.1 General site description

The Jadro River flows from its source at the foot of the Mosor through the alluvial valley and the town of Solin and flows into Kaštela Bay. The total length of the stream is 4.3 km (Figure 3-14). The river forks through the urban area of the town of Solin in several tributaries, whose waters return again to the main bed rivers.

The topographic basin of the river Jadro is relatively small, and covers about 22 km^2. It is an actual hydrological basin much larger. Complexity of underground flows and sizes basins ensure the continuity of this source throughout years. The spring is at an elevation of 34.2 m above sea level, and is being saved groundwater from the further carbonate hinterland. On the source itself affects the water supply of Split for 1700 years, and today for neighbouring cities - Solin, Kaštela and Trogir. Part of the water from the spring is directed to the small one hydropower plant, which is no longer in operation, whose water is being operated they flow into the main riverbed about 300 m downstream from the source.

Remaining amounts of water that are not captured on its own the source flows over the overflow into the main riverbed. Quantities of water abstracted for water supply continuously are measured using limnigraphs set in 1994 on at the very beginning of Diocletian's and the New Channel. For monitoring the flows that remain in the Jadro riverbed, after water abstraction for water supply, data from water stations Vidovića most (1949-1983) and Majdan (since 1984). Vidovića most station was located at bridge of the same name. Slightly more upstream than the bridge is the Majdan station which is in operation today (Figure 3-14).

The CHANGE WE CARE Deliverable 3.1.1 reported the annual time series of air temperature at 2 m and precipitation that are extracted for the area of Jadro River site from the AdriSC climate simulation (1987-2017). Annual values of air temperature range from 13.0 to 14.5 °C, where the last value is reached in 2014. Clear temperature trend can be seen in the series, while annual temperatures can change for about 1 °C between years. The warming trend may be seen in all seasons, while being lowest during winter. Mean temperatures range between 7 and 10 °C during winter, while summer mean temperatures span from 19 to 21 °C. The precipitation rate is changing between 1 and 3 mm/day, i.e. between 400 and 1100 mm per year. The precipitation rate is maximal during autumn, when it might reach 5 mm/day, while the minimum precipitation rate is achieved during summer, when it might go down to 0.5 mm/day, or about 50 mm per season (IOF, 2020).

Bonacci (2012) analysed hydrological data collected in the period from 1 January 1995 to 31 December 2009. Critical situations occur during dry summer months, particularly in July and August, when the natural discharges of the Jadro spring are low, water and air temperatures are high and water demands increase. In these months, sometimes also in September, more than 50 % of the natural discharge is taken from the spring, which is unacceptable from the viewpoint of sustainable management of this water resource. Of particular concern is the strong trend of increase in minimum annual discharges taken from the Jadro spring. Bonacci (2012) highlighted excessive water drainage from the Jadro spring and also alarming trend of increase in water drainage in the past 15 years. The relation between low discharges remaining in the Jadro river bed and high air temperatures was analyzed, and it indicates that there is a real danger of their coincidence and impact on the sustainable development of already very endangered karst environment.

There are no published data on sediment fluxes by the Jadro river stream. However, general observations of the orthophoto images imply a potential contribution of the fine-grained sediment derived from erosion of flysch marls exposed in a quarry situated close to the Jadro River upper stream (Figure 3-15). Besides, construction works in marginal urbanized areas of the town of Solin as well as agricultural activities on the southern slopes of Klis could also contribute to enhanced erosion of the flysch marls and the residual soil developed on the marls. Thus, an occasional increase of the fine-grained sediment fluxes from the topographic catchment to Jadro River is expected. Higher sediment fluxes are expected during rainy seasons, and especially during storms characterized by extreme rainfall. However, direct periodical measurements of both suspended and the bed-load sediment in the Jadro River lower stream and the estuary is missing.

The whole topographic catchment of the Jadro is relatively small and covers about 22 km2, while the agricultural land is generally half of it (Figure 3-15). Agricultural land owned by local inhabitants is situated north of Jadro River upper stream (Figure 3-15). These are mostly oil tree yards, implying that fertilizers, herbicides and pesticides usage is probably not extensive. Thus, several smaller streams and two larger tributaries probably carry some amounts of pesticides from the agricultural land to the Jadro River stream.

The results from the vertical profiles of temperature and salinity (Figure 3-16, Divić et al., 2020) clearly show the salt wedge stratification, which typically occurs in similar estuaries in Croatia, and was previously detected in the River Jadro by other researchers. Such behaviour causes the freshwater to be mostly contained in the upper layer that is consistently decreasing in thickness as one goes downstream, e.g., freshwater layer reaches up to a 1 m depth at the river mouth (vertical profile 1 in Figure 3-16) as opposed to only 20–30 cm at the farthest vertical profile (vertical profile 4 in Figure 3-16).

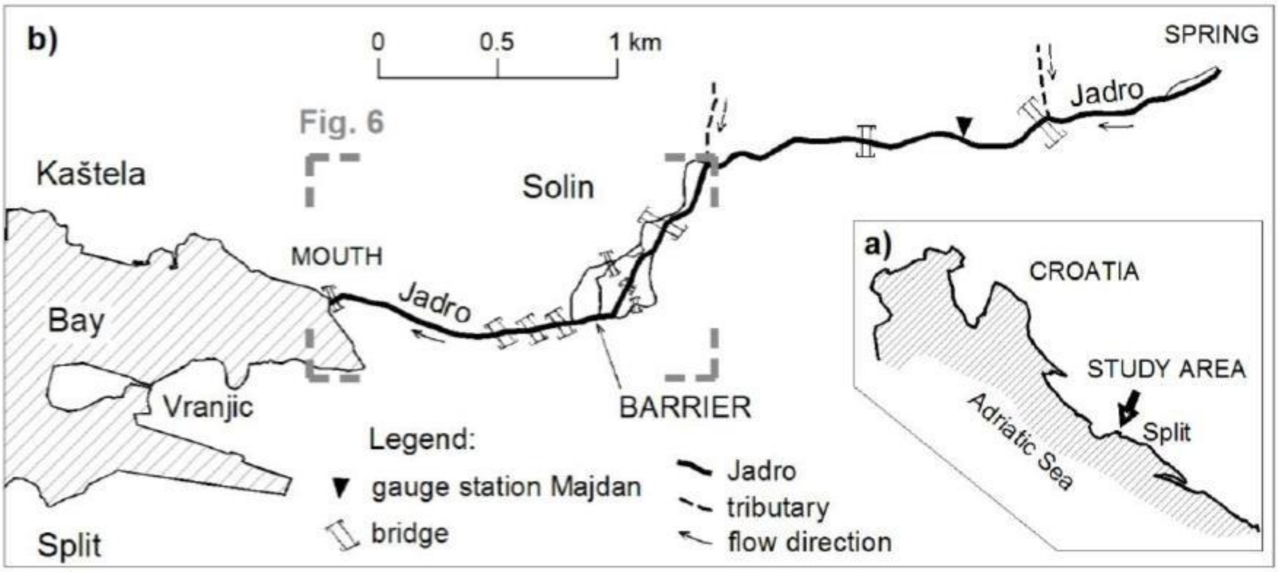


Figure 3-14 Location map of a) the study area and b) Jadro River (after Ljubenkov, 2015).

Figure 3-15 Orthophoto image of Jadro River upper stream (2017). Note a quarry located close to Jadro river upper stream, the agricultural land of Klis area north of the upper stream and marginal urbanized area of town of Solin on the west. Source: DGU (https://geoportal.dgu.hr/).

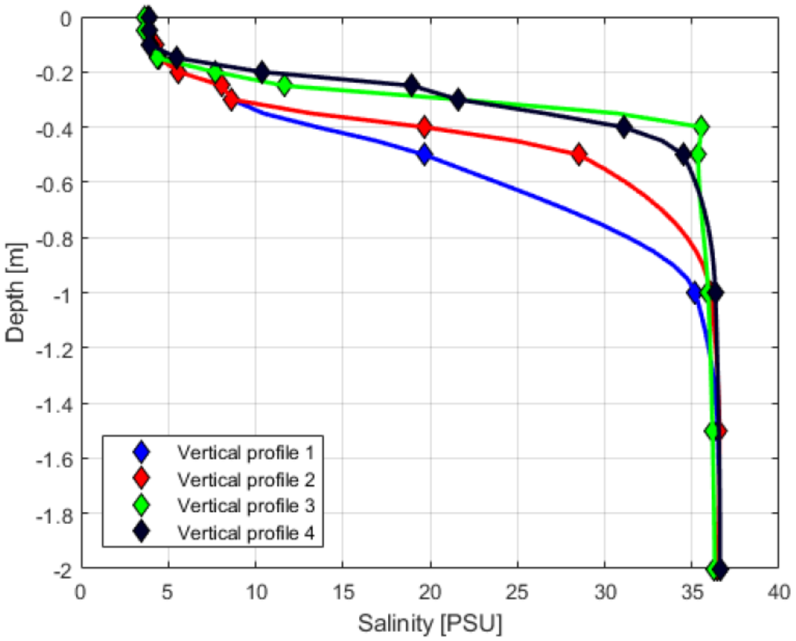


Figure 3-16 Vertical salinity profiles indicating the presence of the salt wedge stratification (Divić et al., 2020)

3.2.2 Assessment of sea level rise scenarios in the considered coastal and transitional areas

Sea level rise is already recorded in the area of Jadro River in the present climate, currently with an amount of about 30 cm per 100 year. Therefore, the duration of floods in the coastal area is more frequent, and the impact of the sea on the coastal area and infrastructure more significant. The most pronounced flooding of the coastal area has been recorded in the last few decades (Figure 3-17).

In the future climate, sea level rise is projected to accelerate to about 50 cm in 100 years. Worst scenarios predict an increase in mean sea level and over 1 meter by 2100, which would have unforeseeable consequences on the coast of the area of Jadro River.

As for the intensity of storm surges and flooding of the coastal area, they will not significantly change the intensity in the future climate (Figure 3-18), rather negative trends are predicted. But combined with rising sea levels, flooding of the coastal area will increase many times over.

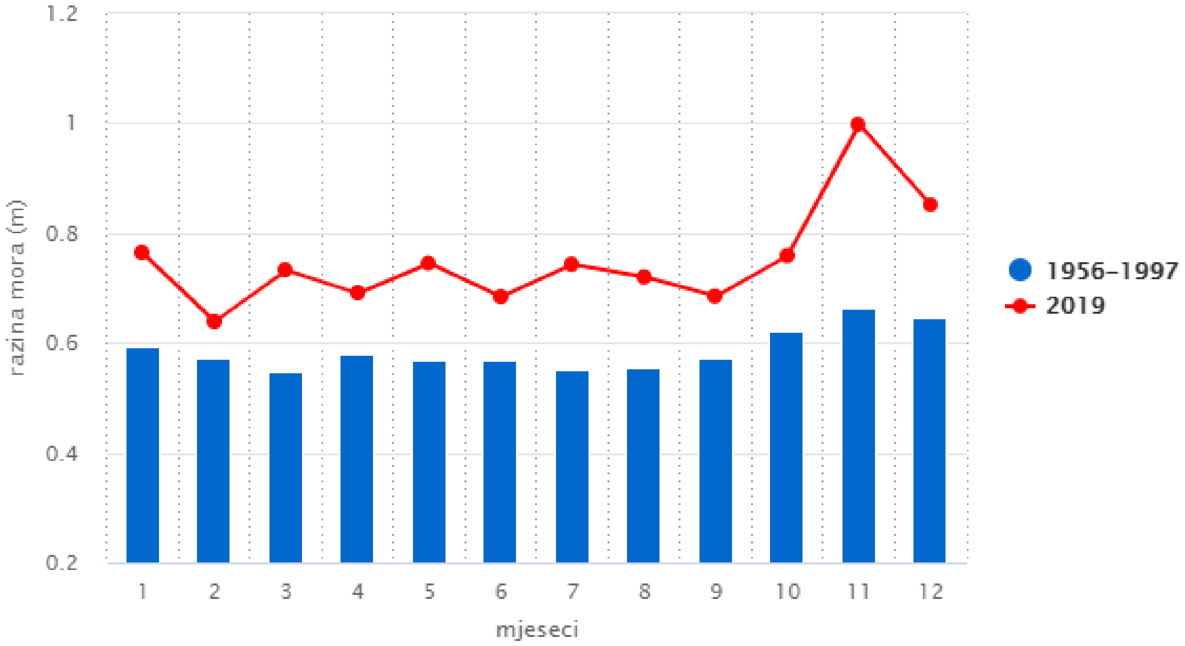


Figure 3-17 Monthly mean sea level (for 2019 and averaged between 1956 and 1997) measured at the Split tide gauge, representative for Jadro River (source: http://baltazar.izor.hr/azopub/bindex

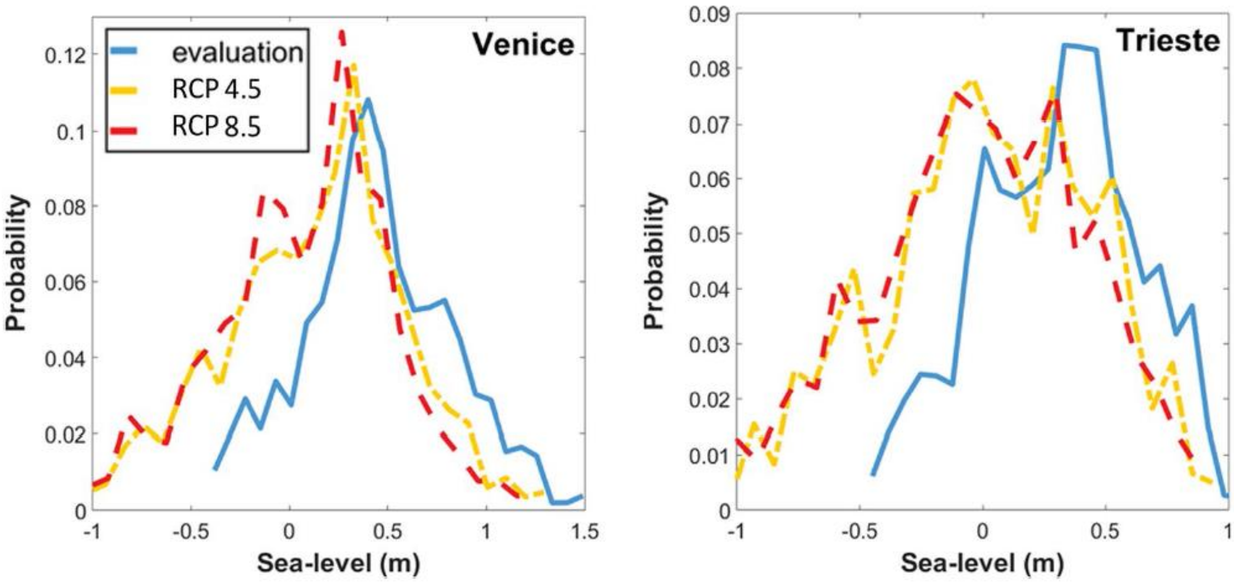


Figure 3-18 Storm surge projections for the strongest sirocco events in the future climate, middle (RCP 4.5) and extreme (RCP 8.5) scenario (source: Denamiel et al., 2020).

3.2.3 Long-term sediment fluxes and identification of erosional and depositional hot spots

Although the amount of eroded material is crucial information for understanding of weathering processes in softer rock masses (flysch marls), there are no previous studies on erosion of flysch in Jadro River topographic catchment. Besides, only few previous analyses of the sedimentological proceses on the pilot-site Jadro River and Vranjic Bay have been done. Buljac et al. (2015) sampled and analysed the uppermost 10 cm of seabed sediment at a few sites across the Kaštela Bay. The easternmost site (site S2) is located in the central part of Vranjic Bay on the coordinates ϕ (N) 43° 31´ 57" and λ (E) 16° 27´ 15" at the sea depth of 18 meters. The analysis revealed that the sediment in the uppermost 10 cm at the site S2 is mud (silty clay or clayey silt) characterized by approx. 50% of siliciclastic material and 40 % of carbonates with some 9% of organic matter. The portion of mud in sediment is decreasing to the west on other sampled sites accross the whole Kaštela Bay, implying that Jadro River supply mostly with fine-grained material (silt and clay).

Recent trends in the sediment stock are poorly known for the Jadro River mouth and the Vranjic Bay. Based on the analyses of the 137Cs distribution in sediment in the Kaštela Bay, Lovrenčić-Mikelić et al. (2017) observed temporal and spatial sedimentation rate variations between three studied periods: 1954–2005, 1963–2005/2006, and 1986–2005/2006. Sedimentation rates were in the following ranges: 0.29–0.49 cm/yr for the 1954–2005 period, 0.58–0.95 cm/yr for the 1963–2005/2006 period, and 0.50–1.32 cm/yr for the 1986–2005/2006 period. The average total sedimentation rates for three periods were 0.41 cm/yr, 0.81 cm/yr, and 0.61 cm/yr, respectively. Long-term sedimentation rate increase in the whole Kaštela Bay was observed and clearly connected to the industrialization and urbanization processes in the coastal area. Lovrenčić-Mikelić et al. (2017) concluded that intensive anthropogenic activities in the coastal area are reflected in the whole bay depending on the amount of the discharged sediment material, topography of the sea bottom, and water currents, and that some localized areas of sediment accumulation may form.

The Jadro River topographic water catchment is mostly covered with soil and vegetation or cultivated fields that reduce the erosion of the flysch marls that characterize the bedrock in the upper stream catchment area (Figure 3-19).

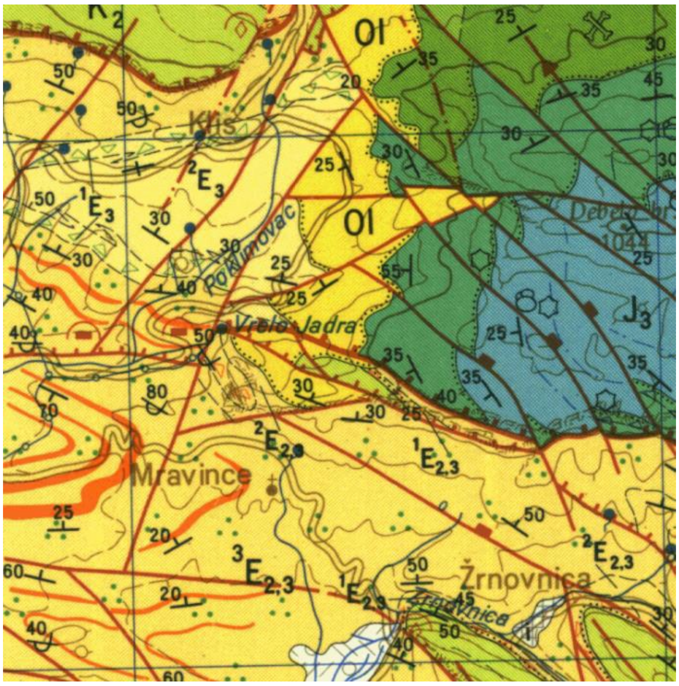


Figure 3-19 Basic geological map (crop from Marinčić et al, 1976) showing impermeable Eocene flysch deposits (in yellow, E2,3) in the Jadro River upper stream topographic catchment. Note two quarries north of the Jadro River. Coordinate grid is 5 km.

3.2.4 Short term and long term vulnerability

The pressures that are the source of vulnerability of the Jadro River delta will be manifested in many environmental aspects, all of them including pressures coming from climate changes and human activities (Margeta et al., 2019). For the latter the effects will be expressed, given that this is a significantly urbanized area, and will primarily concern the coastline itself, the coastal infrastructure and buildings in the coastal area, then on water management, water infrastructure and water supply, including drinking water, human health, tourism, fire, erosion and landslide hazards, as well as the economy related to the sea. Both on land and at sea, climatic pressures will have an impact on the environment and biodiversity, with combined and multiple impacts and interactions, e.g. reduction of terrestrial biodiversity and total plant cover can affect the number and severity of fires, and directly and indirectly on tourism, land infrastructure, and others.

<u>Vulnerability of water resources management</u>. The effects on water resources management will be multiple. Primarily, less precipitation during the summer period along increased air temperature,

combined with the increased number of tourists in the area, will cause increased water consumption. That's where they have to be add an increase in the amount of water that will, due to the same pressures, be used for agricultural activities. Simultaneously, due to the reduction of precipitation, the capacity of drinking water sources will be reduced, and there is a real possibility of problems in the water supply system which is it is necessary to solve in a timely manner through integral solutions in the entire area of Central Dalmatia.

In addition to the above problem, and given the existing solutions and capacity of stormwater drainage water, there is a possibility that the capacity of existing torrential drainage systems will be insufficient. Therefore, in future reconstructions land infrastructure, as well as when planning the construction of either residential or commercial facilities, it is necessary to properly capacity drainage systems and enable natural water runoff with minimal environmental impact in extreme rainfall episodes.

<u>Vulnerability of land infrastructure and buildings.</u> Due to the increase in the intensity of torrential waters in the future climate at the most extreme events, as well as due to the possibility urbanization that will not take into account the proper capacity of torrential drainage, vulnerability of land infrastructure in the area is likely to be increased in the future. In this sense, the effects of climate change can condition negative impacts on road infrastructure as well as its partial destruction, especially in the smaller part bridges and watercourses, due to increased erosion. In addition, in combination with more frequent fires, and given configuration and slope of the plateau on which Jadro is located, landslides are possible in some areas closer to the mountain Kozjak.

<u>Vulnerability of the coast, coastal infrastructure and buildings.</u> The effects on the coast will be in the entire area of Kaštela Bay including Jadro river delta, primarily due to the expected increase sea level. Already now, in situations with stormy south and low air pressure, lower parts of the coast and coastal promenades, especially on parts that have not been rebuilt recently, are being flooded by the waves of the south. Such situations cause shoreline subsidence and erosion, which after prolonged exposure to waves can cause damage and collapse. Similar effects can, of course, depending on the quality of construction, be possible to be expected for other coastal facilities. That's why they have to be further strengthened and protected from submersion of the coast, which includes regular monitoring of the coast and timely decision on remediation in case of documenting damage.

In addition to the built-up parts of the coast, the beaches Jadro River delta will be repeatedly endangered by the erosion of the coast in the case of the projected sea level rise. As tourism is one of the pillars of the economy, it needs to be done appropriate protection of beaches, i.e. to minimize the removal of pebbles into the deep sea, in accordance with the rules of the profession common in such interventions in the world.

The impact of sea level rise will also be reflected in the sewerage infrastructure in the coastal area, as the elevated the level must prevent the discharge of wastewater, in the event that appropriate solutions are not implemented.

<u>Vulnerability of human health.</u> Human health will be most affected by extreme events, especially heat waves during which it is common recording increased mortality and disease in an area. In addition,

extreme rainfall events and storm surges in the coastal area can also have a negative impact on human health, mainly due to sewage spillswater to external surfaces caused by elevated sea levels.

Vulnerability of tourism. The effects on tourism will be twofold. Due to the increase in air and sea temperature, it will be possible to extend the tourist season and in the preseason and in the postseason. In addition, warmer weather will certainly be more attractive to tourists who are not addicted to bathing season, are already attracted by the climate and active holidays in terms of non-marine activities (hiking, cycling inland, etc.). The negative effects will be concentrated in the summer, especially in July and August, when the heat waves will be many times more intense and long-lasting than in today's climate.

Vulnerability of agriculture. Due to the increase in air temperature and heat waves, and the reduction of precipitation in the warm part of the year in the future climate, and thus increased evapotranspiration (evaporation), certain agricultural crops will be endangered, which for their growth and development need more water. This problem can be solved by irrigation, which of course includes appropriate capacity of the entire water supply infrastructure. Although due to the accelerated urbanization the wider Jadro area suitable for agriculture will not be significant, the negative impact will be felt in smaller urban areas agricultural units and backyards of houses where agricultural activities take place.

Vulnerability of terrestrial and marine ecosystems and biodiversity. On land, projected climate change will cause changes in the composition and abundance of plant and animal species, where organisms that are more resistant to high temperatures and prolonged drought periods will prevail over those that are sensitive to changes in environmental parameters. The future climate certainly brings an increase in the number of fires, which will significantly affect the overall degradation of terrestrial ecosystems, as well as the crops that are grown and planned to be grown in the area of Jadro.

In the sea, rising temperatures and salinity will affect biodiversity, especially in the coastal area. It will occur an expansion of thermophilic species towards coastal areas, and the overall abundance of marine plant and animal species will are likely to decrease as a result of changes in primary production, sea acidity, dissolved oxygen and amounts of nutrient salts.

3.2.5 References

Bonacci, O., 2012. Hydrological analysis of water drainage from the karst spring of the Jadro river, Hrvatske vode (Croatian Water), 79/80, 37-42 (In Croatian).

Denamiel, C., Pranić, P., Quentin, F., Mihanović, H., Vilibić, I., 2020. Pseudo-global warming projections of extreme wave storms in complex coastal regions: the case of the Adriatic Sea. Climate Dynamics, 55, 2483-2509. https://doi.org/10.1007/s00382-020-05397-x.

Divić, V., Galešić, M., Di Dato, M., Tavra, M., Andričević, R., 2020. Measurements of surface water properties in an estuary: A case study of River Jadro, Croatia. Water, 12, 209; doi:10.3390/w12010209

IOF, 2020. CHANGE WE CARE project Activity 3.1 Report for Jadro River. Institute for Oceanography and Fisheries.

Ljubenkov, I., 2015. Hydrodynamic modeling of stratified estuary: case study of the Jadro River (Croatia). J. Hydrol. Hydromech., 63, 2015, 1, 29–37. DOI: 10.1515/johh-2015-0001.

Lovrenčić Mikelić, I., Oreščanin, V., Škaro, K., 2017. Variation of sedimentation rate in the semi-enclosed bay determined by 137Cs distribution in sediment (Kaštela Bay, Croatia), Journal of Environmental Radioactivity, 166/1, 112-125, http://dx.doi.org/10.1016/j.jenvrad.2016.03.027

Margeta, J., Baučić, M., Vilibić, I., Jakl, Z., Petrić, L., Mandić, A., Grgić, A., Bartulović, H., Popić, N., Marasović, K., Jajac, N., Rogulj, K., Ivić, M., Jovanović, N., Bačić, S., 2019. Plan upravljanja obalnim područjem Grada Kaštela (in Croatian). Sveučilište u Splitu, Fakultet građevinarstva, arhitekture i geodezije, 152 pp.

Marinčić, S., Korolija, B., Majcen, Ž., 1976. Osnovna geološka karta SFRJ 1: 100 000: List Omiš *Basic geological Map of Yugoslavia 1:100 000, sheets Split– in Croatian], L 33-22. –Institut za geološka istraživanja*Croatian Geological Survey], Zagreb, (1968.-1969.); Savezni geološki institut, Beograd.

3.3 Nature Park Vransko Jezero site

3.3.1 General site description

Vransko lake is the largest lake in Croatia and one of only two large wetlands in the Mediterranean part of Croatia. The area of the Vrana Lake Nature Park, together with the adjacent Jasen floodplain, is a unique natural and hydrogeological phenomenon. Due to its unique natural values, Vransko Lake with its surrounding area, total area of 57 km², was declared a Nature park on July 8, 1999. Due to wildlife biodiversity, especially birds, an 8,65 km^2 area in the north-western part of Lake Vrana, was declared an Ornithological Reserve on February 22, 1983.

Vransko Lake and its basin form a complex hydrological system, with problems caused by climate change / variation, but also a very complex structure and interrelationships of the karst aquifer, the lake system, the sea and the inflow from the basin. For the most part, they are not hydrologically observable, ie their hydrological characteristics cannot be fully measured and precisely quantified. Namely, despite the existence of hydrological monitoring in the basin and on Vransko Lake itself its water balance is only partially hydrologically observable - underground inflows and outflows from the lake system are unknown.

3.3.2 Assessment of sea level rise scenarios in the considered coastal and transitional areas

With the onset of expected climate change / variation, the sea level would rise and the equilibrium between the lake and the sea would be established at slightly higher water levels in the lake. However, such an altitude shift of the entire lake-sea system would not be problematic in itself if the estimated climate changes did not result in an increase in air temperature (and thus increased evapotranspiration in the basin and evaporation from the lake surface) and a decrease in precipitation. All this would have the effect of significantly reducing the inflow into the lake system. This generally reduces the water level in the lake, and prolongs the periods with negative gradients - the penetration of saline sea water into the lake system.

For this area, there are also different scenarios for assessing the impact of climate change, including the impact on sea level rise. Therefore, ways to slow down unwanted processes are considered, as well as adaptations to such changes. Based on the decision of the Croatian Parliament on ratification (OG 55/1996), Croatia undertook the obligations of the United Nations Framework Convention on Climate Change in 1996 and adopted the First National Report of the Republic of Croatia under the United Nations

Framework Convention on Climate Change / UNFCCC / (Ministry of Environmental Protection and Physical Planning, 2001). In this document, the election scenarios of climate change for Croatia are based on two global election scenarios of the IPCC (International Panel on Climate Change), and based on the developed regional climate scenario for the Mediterranean, developed at the University of East Anglia in Great Britain. According to both scenarios, of which scenario 1992a is at the lower limit of expected changes and scenario 1992e is at the upper limit, within the selected time periods until 2030, 2050 and 2100, sea level increases are expected to range from the initial 20 cm (for 2030.) up to 80 cm (for 2100.). Similar results were obtained within the previous pilot project "Impact of projected global climate change on the Cres-Lošinj archipelago" (Ministry of Construction and Environmental Protection, Adriatic Department, 1993) as part of the analysis of climate change scenarios for the Cres-Lošinj archipelago. According to it, the sea level is expected to rise by +18 +/- 12 cm by 2030, by +38 +/- 14 cm by 2050, and by 2100. predicts a total sea level rise of +65 +/- 35 cm.

According to Rubinić 2014. there is a noticeable and very pronounced trend of rising sea levels for all three characteristic annual values both mean and extreme for Prosika -Sea station (Figure 3-20). This trend is fairly uniform at medium and minimum sea levels and is 5.4 cm / 10 yr at minimum and 5.8 cm / 10 yr at medium annual sea levels. At maximum sea levels, this trend is more pronounced and amounts to 8.4 cm / 10 years. Such results, although obtained in a short series of 24 full years (removed from the analysis are1986, 1988 and 1993 due to interruptions in observations), fit into the results of analyses of increasing sea levels at the nearest tide gauge station Split, for which there were longer data sets and an increase trend of 4.15 cm / 10 years was found (Čupić et al., 2011). If the results of the trend analysis from the Prosika tide gauge station were extended to the end of the twenty-first century, the resulting increases fit into the general IPCC (2001) estimates that the mean sea level could rise between 9 and 88 cm, with the mean value of these estimates was 48 cm.

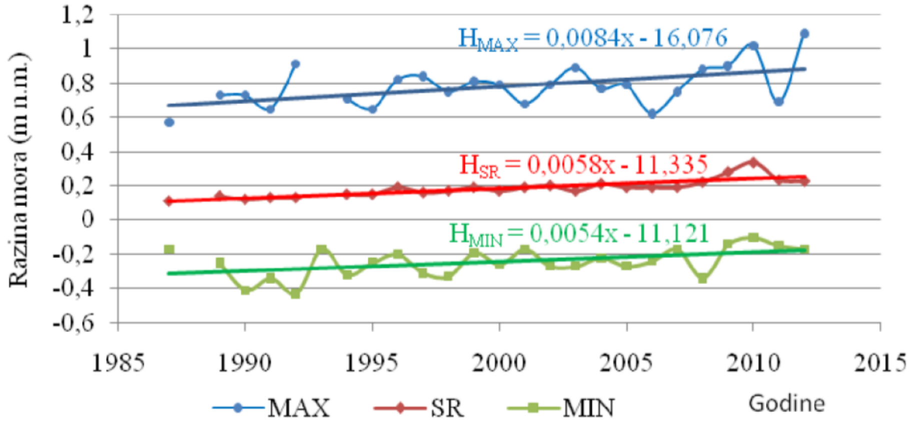


Figure 3-20 Characteristic annual values of sea levels ("MAX" -maximum, "SR" -medium and "MIN" – minimum, y-axis – years, x-axis Sea level m.a.s.l) recorded at the station Prosika - Adriatic Sea (1948-2012) with prominent trends, Rubinić 2014.

The analysis of climatological characteristics by Rubinić (2014.) shows the presence of a global trend of increasing air temperatures, which in the area of influence is about 0.03 °C / year, or even about 2.9 °C / 100 years. with a simultaneous decrease in annual precipitation from 2.0 to 5.9 mm / year, depending on the location in the analysed regional area. Thus, the presence of global trends of increasing sea level was confirmed in the coastal area of the Vransko Lake, where it is shown with a growing trend of 5.8 mm / year. All this affects the amount of water inflow into the lake, its level, but also the quality of water in the lake, like the increase in the share of saline sea water in the lake. The average annual water level in the lake does not have a declining trend, but, depending on the observation period, stagnation or a slight increase. The reason for this is the replenishment mechanism of Vransko Lake, which in conditions of lower water levels in the lake in relation to the sea replenishes the lake with groundwater with large amounts of saline sea water (Figure 3-21).

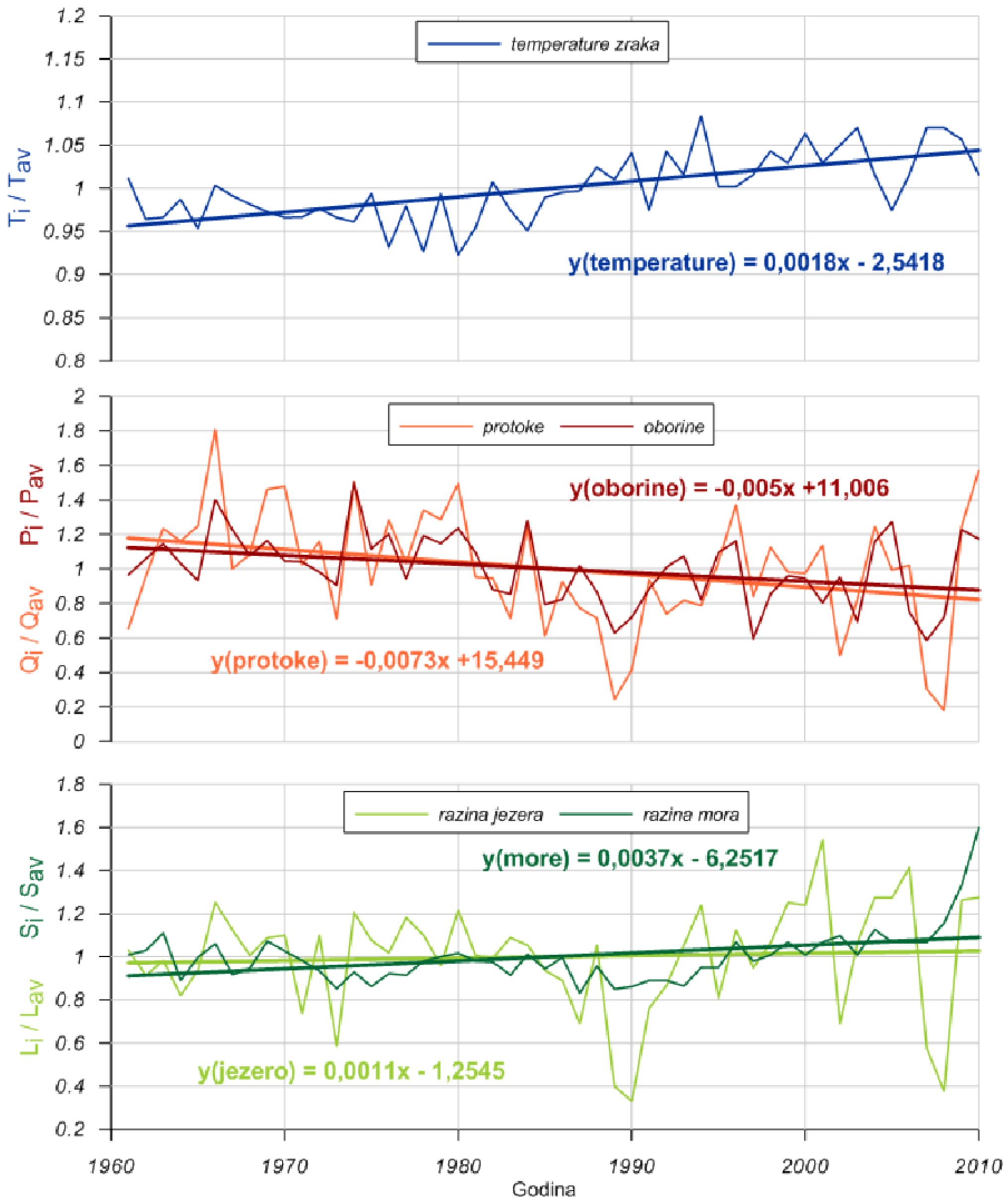


Figure 3-21 Modular values and corresponding trends of characteristic annual values of selected hydrological indicators in the water system of Lake Vransko (1961-2010) x axis – year, y -axis - light green - lake water level, dark green – sea level, red - water inflow, blue – temperature

Despite the decreasing trend of average annual flows, the average annual water levels in Vransko Lake have an increasing trend. If you look at it in a simplified way, it is completely illogical. But there is also a very plausible explanation for the possible cause of such a trend, which is related to the trend of fluctuations in mean annual sea levels, which is also on the rise. Precisely due to the trend of rising sea levels, the entire karst aquifer system, and even Vransko Lake itself, is gradually rising and a new equilibrium is being established between the lake, karst aquifer and the sea. It is a model of the action of coastal karst aquifers in response to climate change / variation and the resulting sea level rise. It should be noted that in the area of Croatian karst, this is a unique example, and even the most direct evidence of the presence and effects of climate change / variation on coastal water resources.

3.3.3 Long-term sediment fluxes and identification of erosional and depositional hot spots

Vransko Lake is dynamically balanced with inflows from the basin and sea level fluctuations, and sedimentation processes play a very important role in maintaining the lake as a predominantly freshwater system. They reduce the dynamics of lake and sea communication by deposited layers at the bottom and sides of Vransko Lake, as well as in the aquifer that separates the lake from the sea where cracks are filled with sediment in conditions of reduced gradient flow.

The conducted research determined the rate of sedimentation in different parts of the lake system. In Ilijanić (2014), sedimentation processes over a longer, geologically speaking historical period are considered. Fajković (2014) considers the dynamics of sedimentation during the recent historical period (1954 - 2010), for which the average sedimentation rate was estimated to be 5.5 mm / year in the north-western part of the lake, and 3.4 mm / year in the south-eastern part. If 4.45 mm / year were taken as the average value, it follows that at the middle level of the lake about 140,000 m^3 of sediment is deposited annually. The yield of terrigenous sediment via watercourses flowing into the lake from Vransko polje can be tentatively estimated on the basis of available monitoring of concentrations and sediment transport, which was carried out by DHMZ at the Lateral Channel and Pakoštane Bridge stations.

There are also estimates of sediment yield in the planned two reservoirs on the watercourses in the Vransko Lake basin, located on the Vransko field. Thus, when estimating the amount of sediment related to the planned reservoir Malo Blato (Elektroprojekt, 2017 a and b) for the profile of the hydrological station Jankolovica on the Main Channel, an estimate of an average of 78,366 m^3 / year of sediment yield from the basin, and when estimating the amount of sediment for the accumulation Gorčina profile of the hydrological station Vrana - Lateral channel 97,596 m3 / year.

Of particular interest is the morphology of the lake bottom which forms a distinctly asymmetric sedimentary body. It has the greatest depths next to the carbonate ridge that separates the lake from the sea on the southeaster side of the lake, especially in the zone of watertight layers that partly follow the contour of the lake shore and south of it is the area of direct communication between the lake and the sea. Precisely because of such currents, sedimentation on that lake side is slow compared to other parts of the lake system where its shallowing is more pronounced, going from the north western part of the lake to the southeast.

Although the sediment yield from the basin is not the dominant component of sedimentation in the lake area, it would be important to monitor the sediment transport to the main tributaries in Vransko Lake (Kotarka and Lateral Channel) because the suspended sediment particles are good sorbents of other contaminants from the basin. However, in order to be able to quantify this sediment yield, it is necessary to ensure adequate flow monitoring on the mentioned watercourses.

Sedimentation processes are extremely important for the preservation of the survival of cryptodepression lakes in coastal karst areas, as well as in general for the protection of coastal karst aquifers from salinization. Namely, in the conditions of the present effects of climate change which are reflected in the rising sea level, the equilibrium state between the groundwater in the aquifer and the sea also rises to higher levels where the fissure systems are more open. However, rising sea levels also cause a slowdown in the flow through coastal karst aquifers, which intensifies sedimentation processes within aquifers. When sea level rise is more intense than the mentioned sedimentation processes within coastal karst aquifers, which is happening in recent times, hydrological connections between the sea and groundwater, and in the case of the lake system, intensify and the risks of salinization are more pronounced, especially due to concurrent inflow reductions. From the Figure 3-22 it can be seen that relatively significant daily sediment flow (of the order of 1 tonne per day) take place during more pronounced water periods, especially when higher waters occur after a longer dry period.

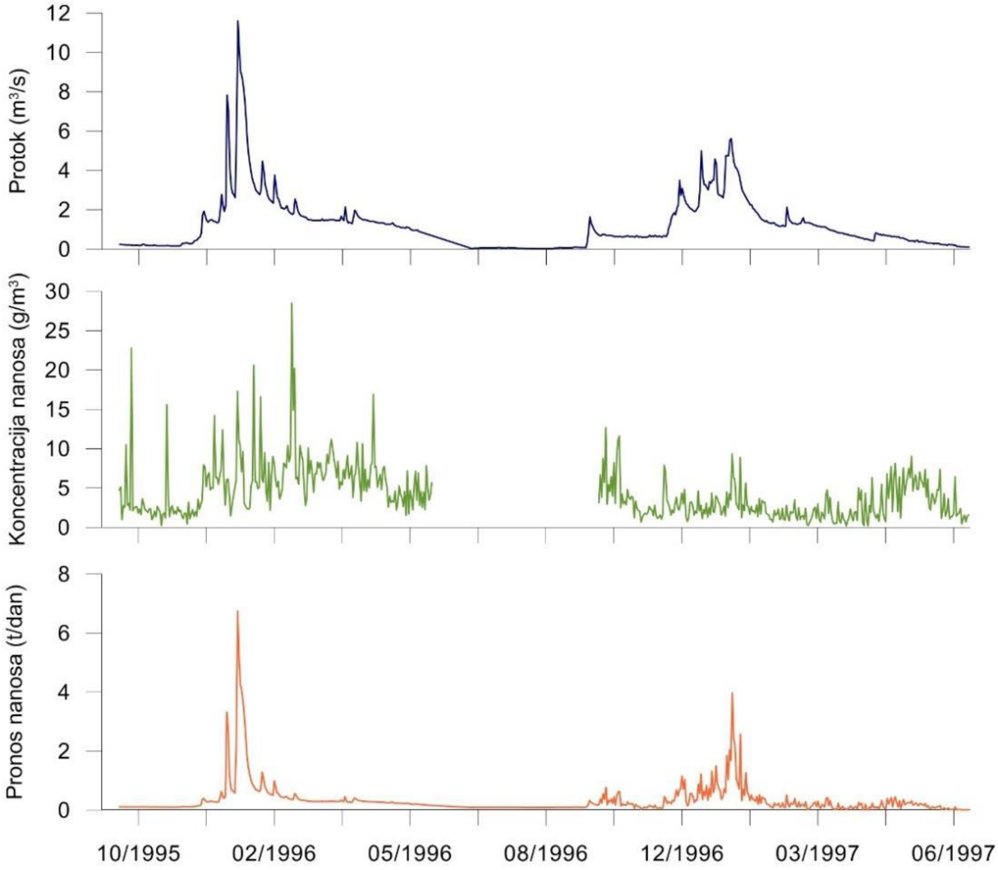


Figure 3-22 Overview of flow, concentration and sediment transport at the Vrana station - Lateral canal (October 14, 1995 - June 30, 1997)

3.3.4 Short term and long term vulnerability

The impact of climate change on Vransko Lake is already evident at the present time (Rubinić and Katalinić, 2014). It was researched for the first time in the work of Rubinić's dissertation (2014), from which the obtained results of the assessment of the possible effects of climatological changes on the flows, as well as on the chloride content, are transferred. Climatological bases of the State Hydrometeorological Institute (Gajić-Čapka et al., 2010, 2011) were developed within the EU project CCWaterS (Terzić et al., 2011, Rubinić et al., 2011). Within this project, based on the available set of measured data from the main climatological station Zadar from 1951 to 2009, an estimate of average annual air temperatures and precipitation for the period from 2010 to 2100 was conducted. Estimates were selected, i.e. time series of mean annual air temperature and annual precipitation obtained on the basis of two regional climate models - REGCM3 (Pal et al., 2007) and Aladdin (Bubnova et al., 1995).

The main climatological station Zadar was chosen because it has a reliable and continuous series of collected data for the entire analysed period after 1951. It was selected as the basic station for the implementation of climate predictions, and is about 30 km away from Vransko Lake and the boundaries of its basin only about ten miles. For the given locality, a comparison of time series data obtained by direct measurement and series from the E-OBS climatological database was performed, and an additional adjustment of the model to local measurements was performed. Climate change is defined as the difference between the future climate (period P1: 2021-2050 and the period P2: 2071-2100) and the reference current climate (period P0: 1961-1990). The results of both models indicate a pronounced increase in mean annual air temperature, while trends in annual precipitation show significantly greater variability in terms of possible sign and amount of change depending on the model and season (Gajić-Čapka et al., 2011). Figures 5.1 and 5.2 give a summary of historical and future generated series of mean annual air temperatures, as well as annual precipitation for the Zadar station for the period (1951-2100). In addition, a statement of the resulting trends for such time series is given, as well as characteristic indicators - mean values and standard deviation for selected characteristic 30-year periods P0, P1 and P2.

In doing so, during further processing, the calculated results of the generated series for 2010 and 2011 were replaced by their actually observed values. In addition to the common tendency of a general decrease in annual precipitation and an increase in mean annual temperatures, these results also have relatively significant differences. The resulting data from 30-year averages for the period (1961-1990) from the Zadar climatological station were compared with the average annual air temperature and the average annual rainfall in the Vransko Lake basin. These data were obtained via a digital map of their spatial distribution and were reduced to the basin itself by the coefficient of interrelation of the mentioned quantities.

The results of the conducted assessments (Gajić-Čapka et al., 2011) show, depending on the applied model, various possible changes in climatic conditions. According to the results obtained using the REG CM-3 model, the average annual air temperatures in the period (2021-2050) could increase compared to the temperatures during the period (1961-1990) by 8%, and during the period (2071- 2100) as much as 22% compared to the reference period. No significant changes (1-2% increase) are expected in the average annual precipitation amounts. The results of the mentioned estimates according to the Aladdin model show that average annual air temperatures during the period (2021-2050) could increase even more markedly compared to the reference period - by about 11%, while for the period (2071-2100) was obtained practically the same value of temperature increase of 22%. However, according to the Aladdin model, the amount of precipitation is expected to decrease compared to the average amount of precipitation during the reference period, by 2% in the period (2021-2050) and by 15% in the period (2071-2100).

Estimates of characteristic values of mean annual inflows for selected 30-year periods are shown in Figure 3-23 the value of the average annual inflow of the historical series (1961-1990) of 4.44 m3s-1 was determined as the average of thirty series of annual inflows generated on the basis of the mentioned method of application of the Langbein method (1962). It is also very close (difference of only 3.3%) to the value of the average annual inflow obtained from the map of the spatial distribution of precipitation and air temperature for the mentioned 30-year period of 4.30 m3 s-1.

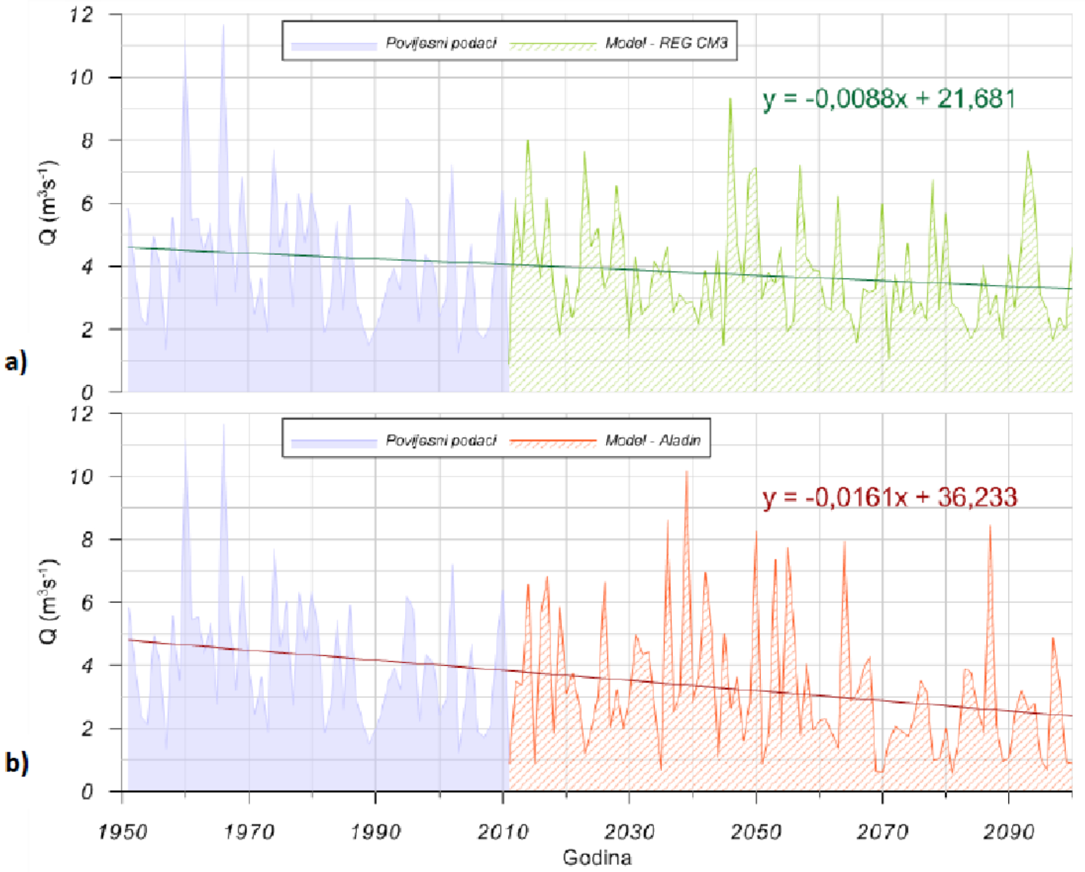


Figure 3-23 View historical data (1951-2011) and data generated by models (2012-2100) series of inflows into Vransko Lake with a corresponding trend for the entire analysed period according to models: a) RegCM3 and b) Aladin (Rubinić, 2014)

It is evident from the given results that the recorded extremes had the character of very low probabilities of occurrence, below 2%, i.e. that the return period of their occurrence was less frequent than the 50-

year return period. However, given the presence of a trend of increasing levels of the Adriatic Sea, and thus raising the level of water oscillations in the lake and its karst aquifer, it is expected that in the future such high levels, but also extreme droughts with low water levels in the lake, be even more frequent.

3.3.5 References

- Bubnova R., Hello G., Benard P. and J. F. Geleyn, 1995: Integration of fully elastic equations cast in the hydrostatic pressure terrain-following coordinate in the framework of ARPEGE/ALADIN NWP system. *Mon. Wea. Rev.*, **123**, 515-535
- Čupić, S. et al., (2011) Climate change, sea level rise on the Croatian Adriatic coast? In: Croatian Waters Facing the Challenge of Climate Change. Zagreb: Hrvatske vode.
- Elektroprojekt (2017a): Preliminary design of the public irrigation system Vransko polje - subsystem Gorčine, Technical solution. (see project Heček, N.), Elektroprojekt, Zagreb.
- Elektroprojekt (2017b): Preliminary design of the public irrigation system Vransko polje - subsystem Malo Blato, Technical solution. (see project Heček, N.), Elektroprojekt, Zagreb.
- Fajković, H. (2014): Influence of Baštijunski brig landfill on the geochemical composition of surface lake sediments of Vrana Lake in Ravni kotari - dissertation, Faculty of Science, Zagreb, 207.
- Gajić-Čapka, M.; Guttler, I.; Branković, Č., 2011. Climate and climate change analyses for CC-WaterS Project. U: Zbornik radova 5. hrvatske konferencije o vodama, Opatija 18.-21.05.2011. Zagreb: Hrvatske vode, str. 109-118.
- Ilijanić, N. (2014): Clay minerals in lake sediments of the eastern Adriatic coast as indicators of environmental changes during the late Pleistocene and Holocene - dissertation, Faculty of science, Zagreb, 382.
- Langbein, W. B., (1962): The water supply of arid valleys in intermountain regions in relation to climate. IAHS Bull, 7(1), str. 34-39.
- Ministry of Environmental Protection and Physical Planning, (2001): First National Report of the Republic of Croatia under the United Nations Framework Convention on Climate Change (UNFCCC). Zagreb: Ministry of Environmental Protection and Physical Planning.
- Pal J. S., et al. (2007), Regional climate modeling for the developing world: the ICTP RegCM3 and RegCNET, Bull. Am. Meteorol. Soc., in press.
- Rubinić J., Radišić M., (2020) Hydrological and climatological research in the Vransko lake Nature park - within the project Change we care
- Rubinić, J., Horvat, B., Terzić, J., Bošnjak, T. (2011): Analysis of climate change / variation in pilot areas in Croatia. In Biondić, D.; Holjević, D.; Tropan, Lj., ed. Croatian waters facing the challenge of climate change: proceedings; 5th Croatian Water Conference, Opatija 18.-21. May 2011. Zagreb: Hrvatske vode, p. 119-128.
- Rubinić, J. (2014): Vrana Lake in Dalmatia and climatic influences. Faculty of Civil Engineering, University of Rijeka, doctoral thesis.
- Terzić, J.; Širac, S.; Miko, S.; Kuschnig, G.; Lukšić, M. (2011): The CC-WaterS project: project presentation with special reference to pilot sites in Croatia. In: Biondić, D.; Holjević, D.; Tropan, Lj., ed. Croatian waters facing the challenge of climate change: proceedings; 5th Croatian Water Conference, Opatija 18.-21. May 2011. Zagreb: Hrvatske vode p. 99-108.

3.4 Banco Mula di Muggia site

3.4.1 General site description

The study area, entirely included in the Municipality of Grado (Friuli Venezia Giulia Autonomous Region) is located between the Grado inlet and the mouth of the Isonzo River, in the Gulf of Trieste, northern Adriatic, Italy (Figure 3-24) (13°24’36” - 13°28’15” East and “45°21’17” - 45°39’30” North. It represents the easternmost part of the system of barrier islands bordering the Grado Lagoon and is nearly entirely devoted to tourism and agriculture. Here, the coastal area has undergone significant changes in historical times due to natural processes but also to anthropic actions i.e. land reclamation and tourism development.

Grado is a tourist town with approximately 8,000 inhabitants, which more than triples during the summer season; the number of nights spent in tourist accommodation is ca. 1.4 million per year (2017). Grado Pineta is a touristic district of Grado having several hotels, restaurants, second houses, and a small marina (Punta Barbacale). Four big camping-resorts with fully equipped beaches are located in the eastern part, between Grado Pineta and the Primero inlet. Most of the beaches are equipped, with services for tourists.

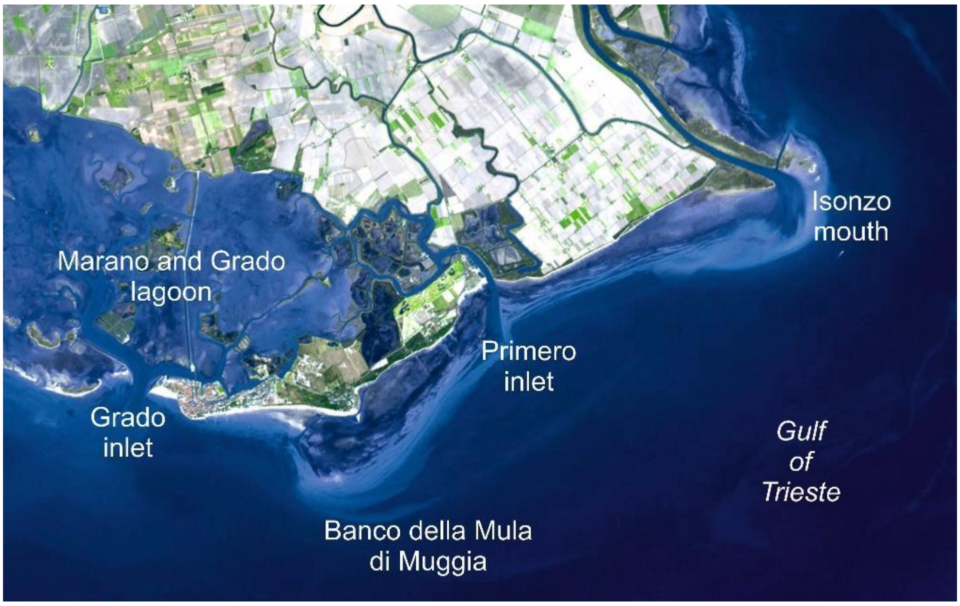


Figure 3-24 Overview of the study area.

The area is well connected by land, air and sea. Two regional routes connect Grado to the highway A4 and Trieste is about 1 hour of trip by car. The Trieste airport is about 20 km and railway stations are at the same distance. A seasonal service connects by boat Grado to Trieste and an efficient cycling network connects the site to the mainland.

The tidal magnitude is unusual for the Mediterranean Sea, with semidiurnal mean and spring tidal ranges of 65 and 105 cm respectively. The passage of atmospheric low pressure systems is able to amplify tidal water levels up to 160 cm: the so called "acqua alta". Climate is temperate, influenced by ENE (Bora) and SE (Scirocco) winds.

The banco della Mula di Muggia is a system of active and relict sand banks, which extends up to 2 km seawards. It can be divided in two parts with arcuate triangular shape divided by the tidal inlet of Primero: the Banco della Mula di Muggia s.s. and the delta complex of the Isonzo River. The Banco Mula di Muggia can be considered as a barrier-island system i.e. an elongate accumulations of unconsolidated sediment that separate the open sea from a landward restricted basin (Figure 3-25). The main sediment source is the Isonzo River, which represent the eastern limit of the study area.

The succession of sandy bars (between -2 m and -5 m) if the Mula di Muggia is arranged in the form of an arc and represents the outer limit of a wide muddy intertidal area partially covered by seagrass (Figure 3-26). Historical data document the presence of the bank morphologies since 1822, long time before the urban development of the area. The present Isonzo delta consists of a delta structure stretched out along the mouth of Sdobba, which became the only distributary channel after the occlusion of the Quarantia branch in 1937. It has a typical river-dominated form, with a single elongate distributary, about 1300 m wide at the base, and 700 m wide at the mouth, extending ca. 1 km in NNW-SSE direction. A series of sandy bars characterize the delta front.

Figure 3-25 Aerial view of the Banco Mula di Muggia.

Figure 3-26 The western part of the Banco Mula di Muggia: the sandy bars and the muddy intertidal zone.

In the pilot site two areas are designated in the Natura 2000 network (Figure 3-27): SPA Valle Cavanata e banco della Mula di Muggia IT3330006 and SPA Foce dell'Isonzo - Isola della Cona IT3330005, both designated also as SAC.

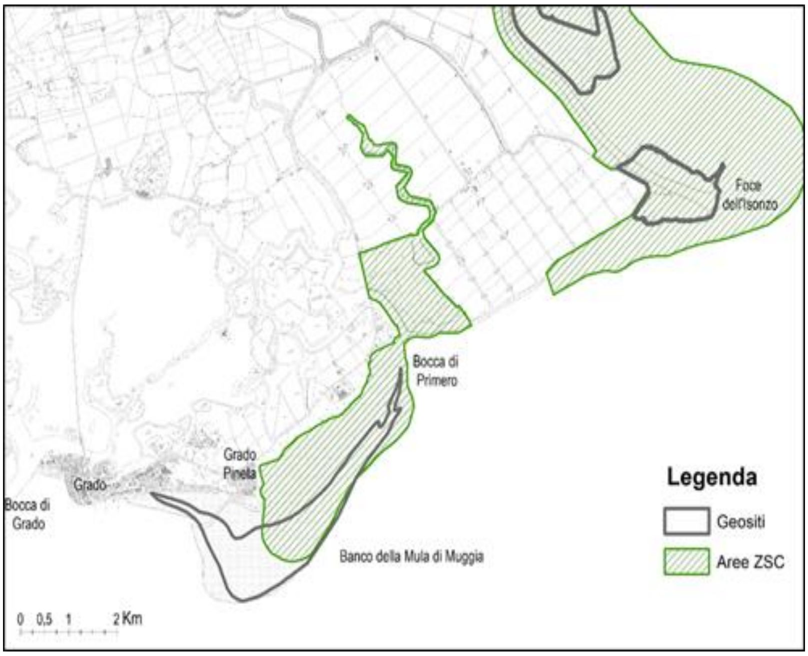


Figure 3-27 Natura 2000 site and geosite perimeter.

3.4.2 Assessment of sea level rise scenarios in the considered coastal and transitional areas

The most recent reports on global climate change (Church et al., 2013; Oppenheimer et al. 2019) warned countries on the risk induced by global sea-level rise (GSLR). This warning must be seriously considered for the assessment of coastal vulnerability and flooding hazard. Due to thermal expansion, ocean dynamics, and land ice loss contributions, sea level rise is not globally uniform and varies regionally with departures of roughly 30% around the GMSL rise (Oppenheimer et al. 2019).

In addition, natural or anthropogenic coastal subsidence at rates of several mm/yr may represent a critical factor for accelerating local coastal changes (Carbognin et al., 2004; Syvitski et al., 2009; Anzidei et al., 2016). Differences from the global mean can be greater than ±30% in areas of rapid vertical land movements. Subsidence caused by human activities is currently the most important cause of relative sea level rise (RSL) in some regions as deltas.

This paragraph provides an assessment of the relative sea level rise scenarios in the considered coastal and transitional areas.

In WP 4.1 in order to take into account for the possible sea level rise in the Adriatic Sea in a RCP 8.5 climate change scenario, a value of 0.70 m has been hired, based on the estimates provided by Antonioli et al. (2017). This estimate is based on the argument that, due to the peculiar properties of the Mediterranean basin (evaporation basin characteristics, hydraulic control at Gibraltar Strait) relative sea level rise in Adriatic region should be smaller than the values envisaged by global estimates.

In order to furnish a more complete framework, in this WP we consider different scenario of relative sea level after an assessment of the different components projected up to 2100: (a) Global sea level rise on the basis of the IPCC projections (Oppenheimer et al. 2019); (b) main land vertical movement i.e. long term trend estimated from geological data, the glacio-hydro-isostatic movement and the recent short-term subsidence.

a) Global sea level rise

The GSLR are obtained from the most recent IPCC projections (Oppenheimer et al., 2019), which reports: *global mean sea level will rise between 0.43 m (0.29–0.59 m, likely range; RCP2.6), and 0.84 m (0.61–1.10 m, likely range; RCP8.5) by 2100 (medium confidence) relative to 1986–2005*.

Regarding the Mediterranean Sea, the discussion reported in Zanchettin et al. (2020) suggest that sea-level rise (evaluated by using dynamical and statistical models) will only have small deviations (less than 10%) from the global-mean value.

With regard to more severe (high-end) sea level scenarios, Rahmstorf (2007) suggests a maximum level of about 1.4 m, using a semi-empirical relation that connects global sea-level rise to global mean surface temperature. Thiéblemont et al. (2019) shows that, by 2100, Northern Adriatic MSL could unlikely but possibly rise by more than 1.8 m, by selecting the highest physical-based estimate found in the literature for each sea-level component. Therefore, although high-end GMSL rises (up to 2 m at the end of the 21st century) are difficult to define from a rigorous scientific perspective in terms of amplitudes and probabilities, they are important in most instances (e.g., Nicholls et al., 2014, Stammer et al. 2019). There is, in fact, a significant demand for a "worst-case" scenario of sea level rise for planning purposes and investment decisions, as it frames the greatest risk, largest damages, and highest prospective costs in planning adaptation.

In order to better contextualize the phenomenon of sea level rise in the North Adriatic, we reported in Figure 3-28 the sea level data registered by the tide gauge of Trieste, with the position of the real sea level in the IPCC reference time (relative to 1986–2005with a mean level of -4.3 cm below the IGM datum Genova 1942). In the *Table 1* a synthesis of the data is reported.

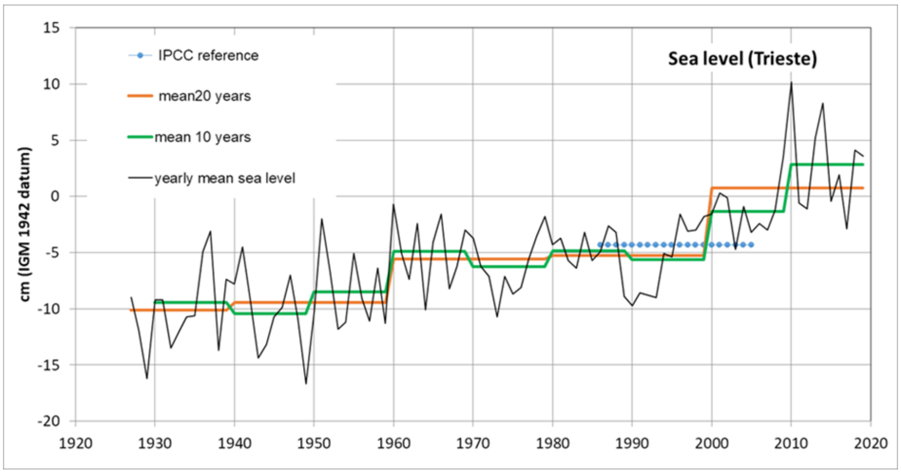


Figure 3-28 Mean sea level registered by the tide gauge of Trieste during 1927- 2019 (data from CNR Trieste available on https://www.psmsl.org/data/obtaining/stations/154.php), the position with respect to the IGM 42 datum is obtained from the information reported of Stravisi & Purga, 1997.

year 1	year 2	sea level change (cm)	rate (mm/y)
1899	1919	4.2	2.1
1919	1939	3.2	1.6
1939	1959	0.8	0.4
1959	1979	2.2	1.1
1979	1999	2.4	1.2
1999	2019	6.7	3.4
1899	2019	19.5	1.6
1939	2019	12.1	1.5

Table 1 – Mean sea level rise (cm) and relative rate at 10 years – intervals as measured by the Trieste tide gauge.

The **isostasy values** derive from the model published for Italy by Lambeck et al. (2011), which indicates for the study area a rate of 0.125 mm / year.

The **tectonic values** (as reported by Antonioli et al. 2017) derive from bibliographic data referring to long and short term stratigraphic levels (respectively: MIS 5.5 = 125000 years, late Olocene = 5000 years). The area between Trieste and Caorle shows a tectonic response averagely between 0.3 and 0.5 mm/year, it was therefore considered an average value of 0.4 mm/year.

The **short-term subsidence** represents a more controversial issue. In the case of the coastal area of Friuli Venezia Giulia, natural and anthropic processes interact. Regarding the induced subsidence, groundwater withdrawals, hydraulic reclamations and urbanization are the most common causes of land subsidence.

An evaluation of the short – term subsidence rate was carried out, based on topographical data by the Protezione Civile of the Friuli Venezia Giulia (2010). According to the data of the Civil Protection the phenomenon of subsidence (referred to the period 1980-2007) affects the lower Friuli plain, with particular reference to the coastal arc (4 mm / year in Lignano to 7 mm / year in Grado), the Tagliamento mouth (around 4 mm / year), the Isonzo delta (with peaks up to 5 mm / year). The high values can be attributed to the fact that the levelling benchmarks were almost always located on the lagoon banks, which are often subject to collapse and increased subsidence due to the high compaction of the soil due to their own weight.

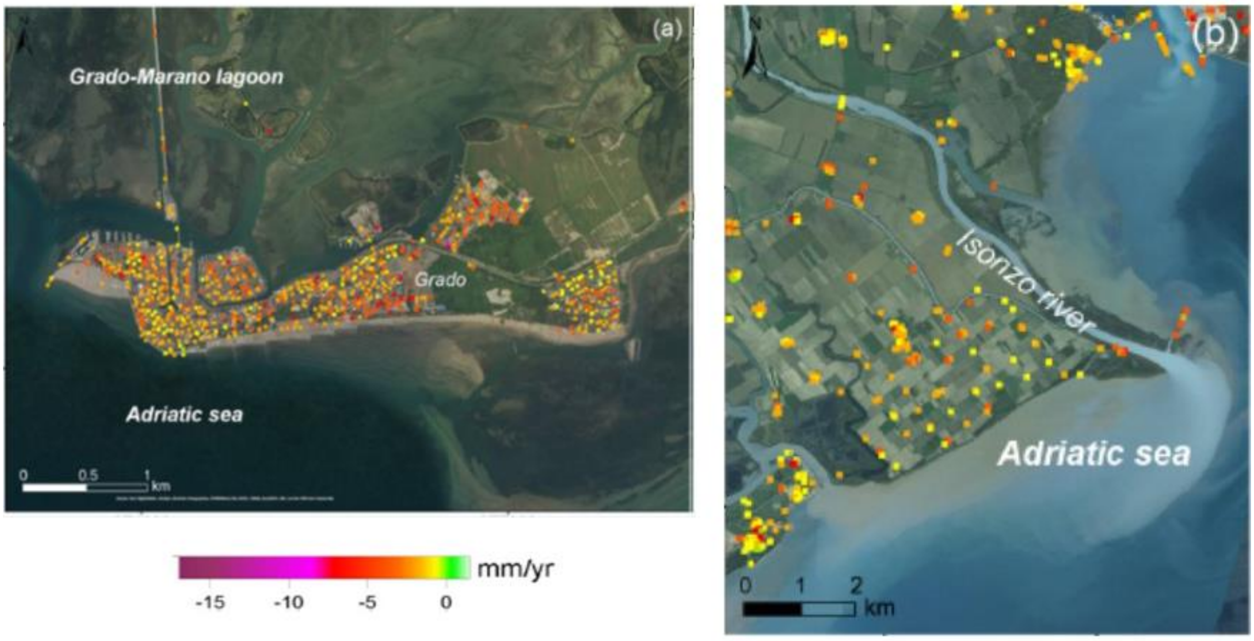


Figure 3-29 Details of the average land displacements over the period 2003–2010 at the Grado littoral and the Isonzo River mouth (from Da Lio and Tosi, 2018 https://doi.org/10.1016/j.scitotenv.2018.03.244).

In most recent time, sinking rates in the FVG coast were evaluated through the interferometry methods by Da Lio e Tosi (2018). The analysis is based on Persistent Scatterers Interferometry (PSI) products, obtained by Envisat ASAR (2003–2010) and ERS1/2 (1993-2000) images and made available by the National Geoportal of the Italian Ministry of the Environment and Protection of Land and Sea (http://www.pcn.minambiente.it/mattm/en/). The recent land subsidence (2003–2010 period) confirms the older data with an eastward decreasing trend on the littoral strip from Bibione to Monfalcone. However, high sinking values have been observed locally along the whole littoral. The subsidence of the eastern littoral sector encompassing Grado, the Isonzo River mouth and Monfalcone is characterized by high variability, although the average subsidence spans from 2 and 2.5 mm/year), sinking rates as high as 10 mm/year at Grado, 4 mm/year in the Isonzo estuary have been detected (Figure 3-29).

More recently, the Servizio Geologico of the Regione Autonoma Friuli Venezia Giulia has entustered Planetek Italia with the multitemporal interferometric elaboration (MT-Insar) of COSMO-Skymed satellite SAR scenes, both in ascending and descending orbit, relative to the subsidence of the coastal area of the Friuli Venezia Giulia Region.

The monitoring activity was carried out through the service Rheticus® Displacement. Interferometric analysis has allowed to obtain a good density of measuring points over the entire monitored area. Both Distributed Scatterers (DS) and Persistent Scatterers (PS) were analyzed, obtaining displacement measurements.

In addition to COSMO-Skymed images captured in HIMAGE mode [RD3] in the period February 2011 - January 2020 in ascending and descending orbit, the Sentinel-1 images, acquired in IW mode [RD4], in the period April 2015 - May 2020 were processed both in ascending and descending orbit. Interferometric maps obtained from Sentinel-1 data were compared with average speed values from permanent GNSS stations within the area, obtaining an excellent level of agreement between the estimated differential movements with Sentinel-1 interferometric measurements and GNSS. Finally the Sentinel-1 maps were compared with the COSMO-Skymed maps, obtaining also a good level of agreement.

Some example of maps of the average speed distribution are shown in Figure 3-30, Figure 3-31, Figure 3-32, and a data synthesis is presented in *Table 2*. The available measurements show a situation of stability (compared to the reference point) with some local instabilities characterized by rather modest average speed values (a few mm/year).

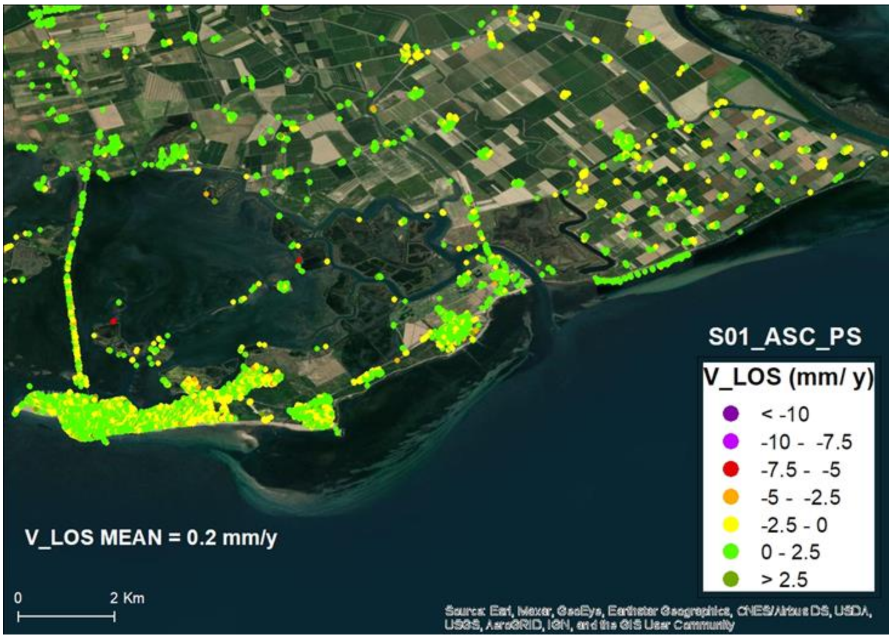


Figure 3-30 Average land displacement (V_LOS) obtained from Sentinel 1 (ascending orbit for Persistent Scatterers April 2015- May 2020).

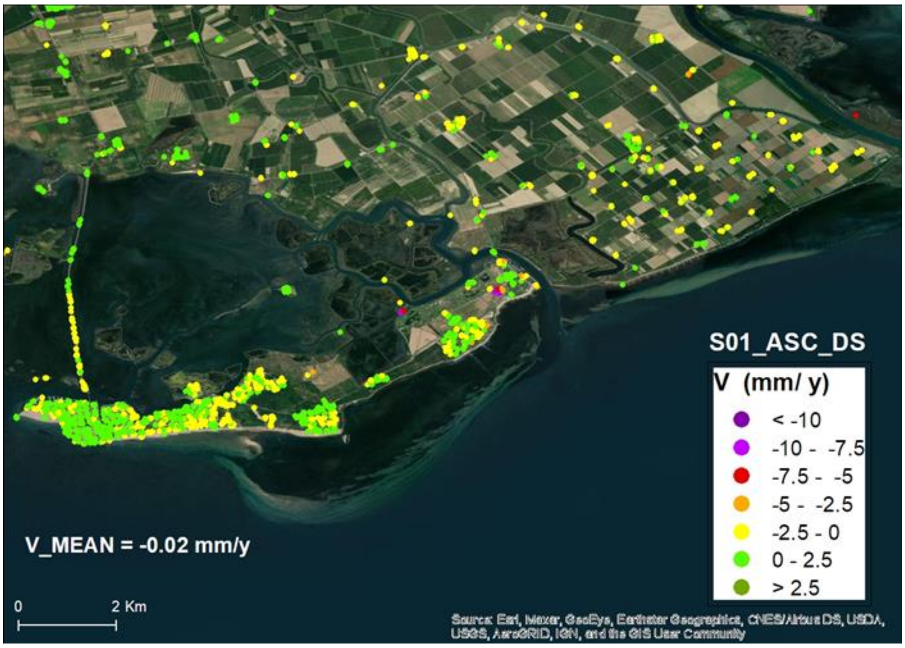


Figure 3-31 - Average land displacement obtained from Sentinel 1 (ascending orbit for Distributed Scatterers April 2015- May 2020).

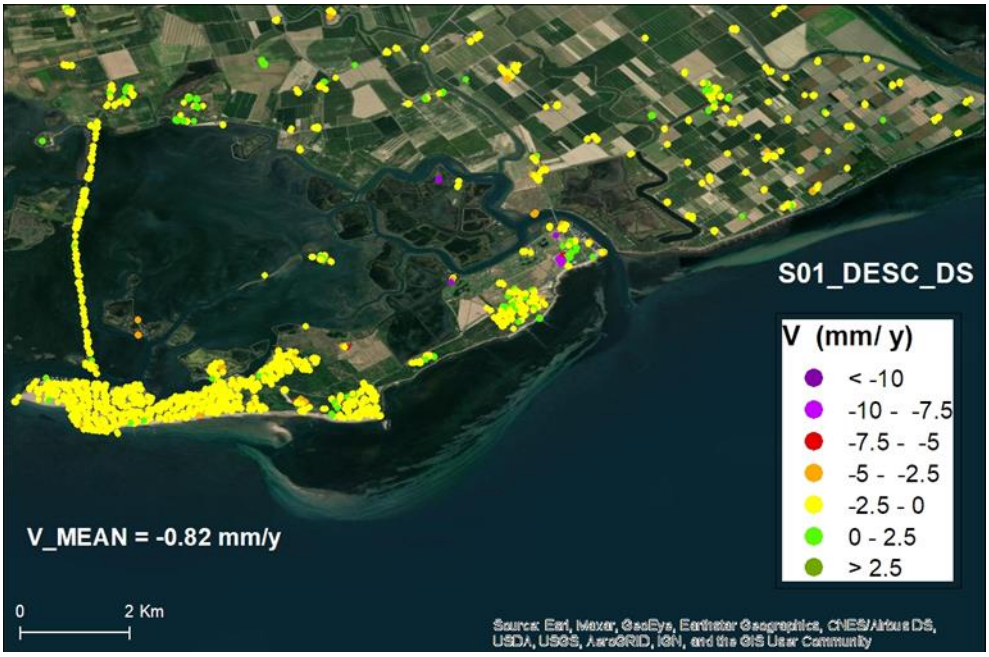


Figure 3-32 Average land displacement obtained from Sentinel 1 (descending orbit for Distributed Scatterers April 015- May 2020).

Data	Scatterer count	V mean (mm/y)	V standard deviation (mm/y)
Sentinel 1 _ASC_DS	1469	-0.03	1.11
Sentinel 1 _ASC_PS	18 718	0.2	0.9
Sentinel 1 _DESC_DS	1 852	-0.8	1.16
Sentinel 1 _DESC_PS	21 575	-0.6	0.94
Cosmosky_DESC_DS	15 339	0	0.87
Cosmosky_DESC_PS	107 403	0.18	0.84

Table 2 - Average land displacement obtained from interferometric data in the Grado area.

These results indicate a substantially stable situation in the examined area and disagree with those, above presented, of Da Lio and Tosi (2018).

Due to the discrepancy in the interferometric data results, we assume the long – term land movement defined by Antonioli et al. (2017) from geological data here.

The adopted sea level rise scenario to 2100 are presented in the *Table 3* (a) and two high-end scenarios are considered in *Table 3* (b).

a)

2100 scenario	GSLR (cm)		long term land vertical movements		glacio-hydro-isostasy		total RSLR to 2100
	GSLR (cm)	SLR IGM 42 (cm)	rate (mm/y)	change (cm)	rate (mm/y)	change (cm)	(cm)
IPCC 2013 RCP 2,6 min	29	24.7	0.4	3.3	0.125	1.0	29.0
IPCC 2013 RCP 2,6 average	43	38.7	0.4	3.3	0.125	1.0	43.0
IPCC 2013 RCP 2,6 max	59	54.7	0.4	3.3	0.125	1.0	59.0
IPCC 2013 RCP 8,5 min	61	56.7	0.4	3.3	0.125	1.0	61.0
IPCC 2013 RCP 8,5 average	84	79.7	0.4	3.3	0.125	1.0	84.0
IPCC 2013 RCP 8,5 max	110	105.7	0.4	3.3	0.125	1.0	110.0

b)

2100 high-end scenario	GSLR (cm)
Rahmstorf, 2007 max	140
Thiéblemont et al., 2019	180

Table 3 – (a) Total Relative sea level scenario projected up to 2100 (cm) resulting from the sum of: Global sea level rise (GSLR) on the basis of the IPCC projections (Oppenheimer et al. 2019) in absolute values and referred to the Italian IGM 42 datum; long term land vertical movement as reported by Antonioli et al. (2017); isostasy values derive from the model published for Italy by Lambeck et al. (2011), which indicates for the study area a rate of 0.125 mm / year. (b) Global sea level rise (GSLR) according to high-end scenarios of Thiéblemont et al. (2019).

Besides sea level rise, wave climate and its variations can play an important role in controlling coastal dynamics and possibly affecting the stability of the coasts and the safety of the infrastructures. At the present stat of the art, a local assessment of the future wind wave regimes in the nearshore is not available. Nevertheless, some important indications can be obtained from Der 4.1, which includes an analysis of the effects of climate change on hydrodynamic processes at the Adriatic basin scale and offshore of the Pilot Site of Mula di Muggia.

Mean conditions are studied by means of the SWAN modelling system, based on the implementation of a climatological control run for 1971-2000 and a run under the IPCC RCP8.5 climate scenario for 2071-2100 (Chapter 4.1.3). Predicted significant wave height statistics consists in a decrease in mean, calm, and storm conditions throughout the Adriatic basin, but with the exception of an increase in the extreme values along the northeastern coastal regions, associated with the variations in Sirocco wind regimes. This local effect is attributed to the higher relative weight of Sirocco with respect to Bora due to a northbound migration of the Mediterranean cyclone tracks (Bonaldo et al. 2020). At the Banco della Mula di Muggia, the relatively shallow seabed and the partially sheltered position at the edge of the Gulf of Trieste tend to limit the severity of the wave storms impacting the coast. Nonetheless, a statistically significant increase of approximately 20 to 30% is actually expected in the autumn and winter months, alongside a reduction of Hs in the calmer summer conditions. The intensification of winter sea state severity is associated with an intensification of extreme southerly storms.

The Project dataset can be used as a boundary condition for very high-resolution downscaling for local applications. Dedicated high-resolution modelling efforts can be necessary in order to properly account for the spatial variability of the processes and their drivers.

3.4.3 Long-term sediment fluxes and identification of erosional and depositional hot spots

The analysis reported in the Derivable 3.2.1 and 3.2.2, regarding the morphological and bathymetric configuration of the pilot site, has allowed describing the evolution of the coastal system, quantifying the sedimentary budget (updated to 2019) and identifying the presence of depositional and erosional hotspots. At the same time, we present here an update of the sedimentological pattern as results of the sampling campaign carried out during 2020-21 and the results of the study on the morphodynamics and hydrodynamics via numerical modelling carried out by the Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum Università di Bologna.

Finally, a summary of the existing data and hypothesis about the sediment supply driven by the Isonzo River allow us to complete, as well as possible, the main elements of the sedimentary dynamics in the area.

3.4.3.1 Sediment budget based on morpho-bathymetric analysis

The Grado area is characterized by two protrusions of the isobaths represented by the sedimentary structures of the Banco della Mula di Muggia barrier system and the delta of the Isonzo River, where the Holocene sediment thickness reaches the 8 m (Figure 3-33) (Trobec et al., 2017).

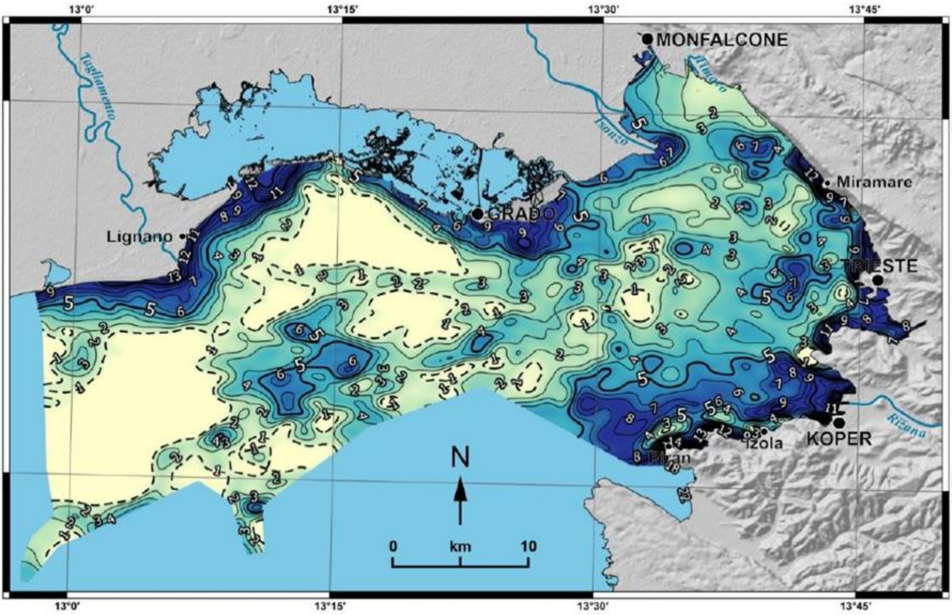


Figure 3-33 The thickness of Holocene marine sediment in the Gulf of Trieste (in meters) (da Trobec et al., 2017)

Historical and recent data indicate that the structure has been preserved over time, migrating westward.

The 3.4.3 (Derivable 3.3) paragraph provides an estimate of net long-term sediment fluxes based on the topo-bathymetric profiles (described at Derivable 3.2.1) from 1968, 1985, 2007 and 2019 and the relative DTM (Digital Terrain Model).

In contrast to the trend of rising sea level, the sediment budget data indicate a significant sedimentary flow conveyed towards the western side of the Mula di Muggia. The distribution of accumulation rates is inhomogeneous: most of the accumulation takes place on the western limit of the Banco area (P4 profile), while the accumulation rates towards the inlet of Grado are gradually lower (Figure 3-34). Despite the absence of erosional hot spots, some of the touristic beaches of Grado are periodically subject to noticeable sand loss as consequence of storms and surge. For this reason, in the last twenty years, 3 nourishment works have been carried out:

- 2005: 75 000 mc (Grado beach)

- 2013: 20 000 mc (Grado beach)
- 2019: 70 000 mc (Grado beach, Grado Pineta beach).

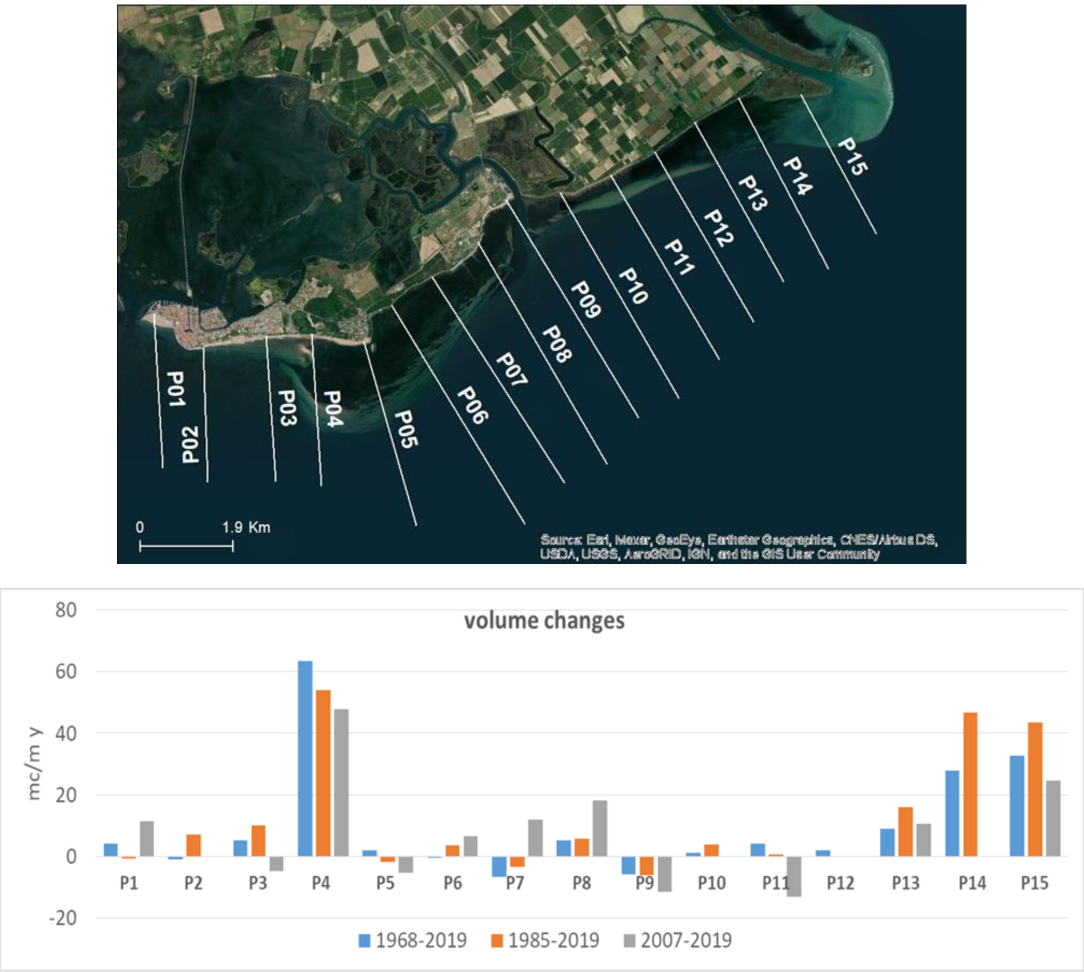


Figure 3-34 Volume changes along profiles for different time intervals.

3.4.3.2 River input

The sediments conveyed to the mouth by the Isonzo River are transported by the dominant wave regime (Bora and Levante) towards Grado, at first by-passing the Primero inlet and the whole central body of the Banco, to deposit at its western side, which acts as a sedimentary trap.

The Isonzo River is the most important sediment source in the area. The catchment basin of the Isonzo has a total extension of about 3,452 km^2, with important tributary (Natisone – Torre and Vipacco Rivers). Even if there are no data about it, some elements support the hypothesis of a significant potentiality of the river solid discharge: the torrential regime of the river that collects and discharges the waters of the southern slope of the Julian Alps and the very high rainfall of its Pre-alps catchment (mean yearly rainfall between 2.700 and 3.200 mm).

Instead, severe anthropogenic modification (afforestation, river damming, and sand mining on the river-bed) are responsible for an important decrease of the fluvial sediment load over the last century, as reported by some Authors (Regione Autonoma Friuli Venezia Giulia, 1985; Siche & Arnaud - Fassetta, 2014). The decrease is not documented by direct measures but is supported by the evidence of morphological changes on the river bed (Siche & Arnaud - Fassetta, 2014).

The lack of data on the sedimentary input to the coast from the Isonzo river do not allow to compare the coastal budget and the river supply.

A very rough estimate of the sedimentary supply of the Isonzo River has been made, within the CAMIS project (Regione Autonoma Friuli Venezia Giulia, 2014), using the flow measurement and estimation data of solid transport (ADCP and water samples of 2014 at the Peteano section). An approximately 800.000 tons/year were quantified, correspondent to (assuming a density of the fine material of the order of 1.800 kg/m^3) 440.000 m^3/year.

Another estimate was made by Brambati (Regione Autonoma Friuli Venezia Giulia, 1985) applying the indirect method of Gravilovic that defines the potential of solid material potentially erodible and transportable within a basin. After a correction for the presence of dams and artifacts, the Author estimated a final positive balance of 817.000 m^3/ year, despite a sediment mining from the river bed of 760.000 m^3/ year.

As part of this project, an Acoustic Doppler Current Profiler (ADCP) was installed on the river bed In order to evaluate the solid discharge of the Isonzo River, near the mouth. The installed ADCP is a TELEDYNE RD INSTRUMENTS WorkHouse Mariner. The instrument was positioned on the bottom of the river at coordinates N 45°43'51.8" E 13°32'05.9" and was solidly connected to a pole on which a photovoltaic panel is placed to keep the instrument in operation continuously.

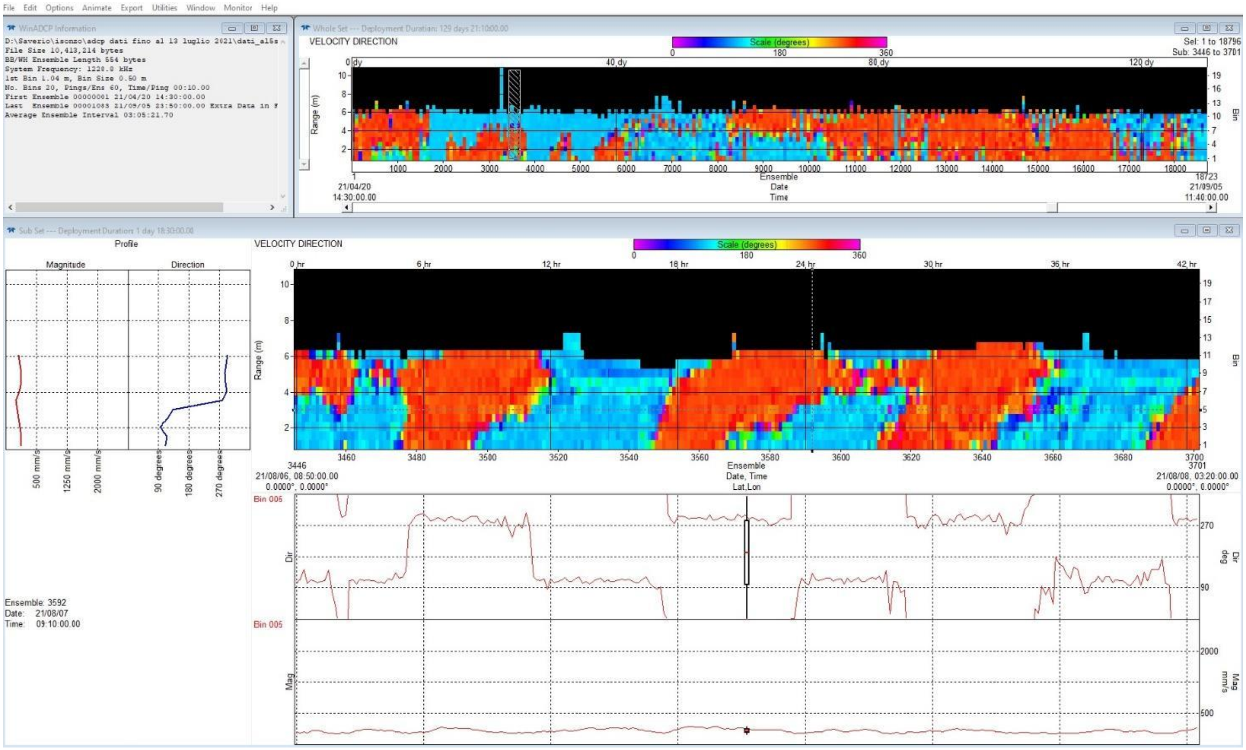
The instrument consists of 4 sensors with different orientations and continuously records the speed and direction of the current and the intensity of the signal (echo-intensity) with a sampling interval of 10 seconds. These values are measured for each level (bin), starting from the distance of 1.05 m from the instrument up to the distance of 10.54 m, with a step of 0.50 m between one level and the next, for a total of 20 levels: the distances are calculated with respect to the direction of the instrument (in this case the vertical direction from bottom to top). The output data is provided by the instrument with an interval of 10 minutes as an ensemble of 60 data recorded every 10 seconds.

The presence of 4 sensors, more in number than the 3 needed to measure the direction of the current, makes it possible to evaluate the error and increase the quality of the data.

Although the instrument does not directly detect the solid discharge values, it is possible to correlate the echo intensity values with the turbidity detected with direct methods in various flow conditions, generating a calibration curve from which to derive, thanks to the velocity values of the current and the section of the river bed, the solid transport.

Data collection started on 20/04/2021 at 2.30pm and is currently running. The data provided by the ADCP are downloaded daily.

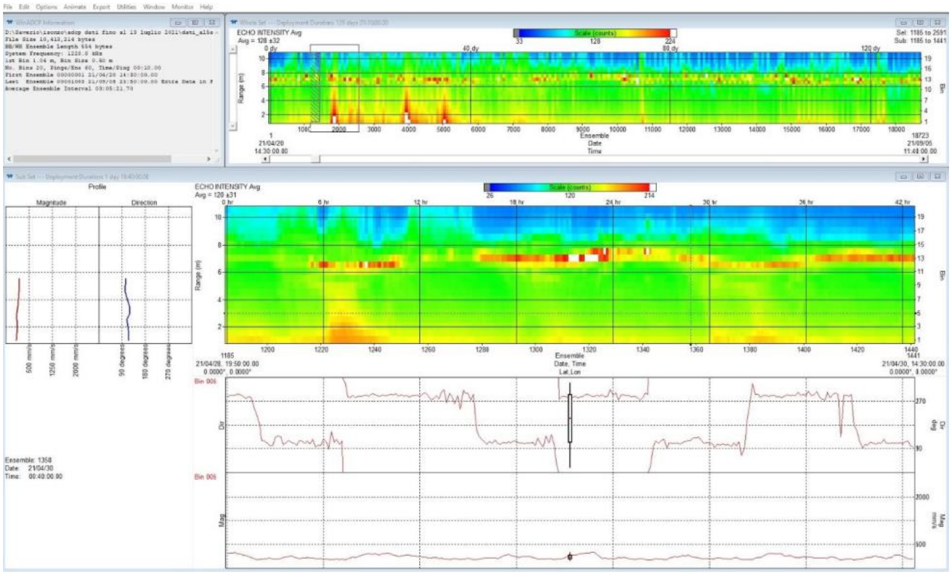
A single file from daily data using *MergeFile* software was created. TELEDYNE RD INSTRUMENTS WinADCP software was used for data analysis. The graphic interface of the software makes it possible to view the variation of the parameters over time (Figure 3-35, Figure 3-36). Through WinADCP we exported the data in *.txt* format in order to be analyzed and processed (it's possible to export in *.mat* format also). An example of processing using Microsoft Excel is shown in Figure 3-37 in which three flood events can be identified.



```
D:\Saverio\isonzo\adcp dati fino al 13 luglio 2021\dati_al5s
File Size 10,413,214 bytes
BB/WH Ensemble Length 554 bytes
System Frequency: 1228.8 kHz
1st Bin 1.04 m, Bin Size 0.50 m
No. Bins 20, Pings/Ens 60, Time/Ping 00:10.00
First Ensemble 00000001 21/04/20 14:30:00.00
Last  Ensemble 00001083 21/09/05 23:50:00.00 Extra Data in F
Average Ensemble Interval 03:05:21.70
```

```
Ensemble: 3592
Date:    21/08/07
Time:    09:10:00.00
```

Figure 3-35 - WinADCP graphical interface. The current direction over time is displayed in the interface. The blue and red areas represent opposite directions that are generated due to the intrusion of the saline wedge.



```
D:\Saverio\isonzo\adcp dati fino al 13 luglio 2021\dati_albe
File Size 10,413,214 bytes
BB/WH Ensemble Length 554 bytes
System Frequency: 1228.8 kHz
1st Bin 1.04 m, Bin Size 0.50 m
No. Bins 20, Pings/Ens 60, Time/Ping 00:10.00
First Ensemble 00000001 21/04/20 14:30:00.00
Last  Ensemble 00001083 21/09/05 11:50:00.00 Extra Data in F
Average Ensemble Interval 03:05:21.70
```

```
Ensemble: 1358
Date:   21/04/30
Time:   00:40:00.00
```

Figure 3-36 - WinADCP graphical interface. The echo intensity over time is displayed in the interface. The high intensity band (red, yellow and white) at about the 13th bin represents the water-air interface.

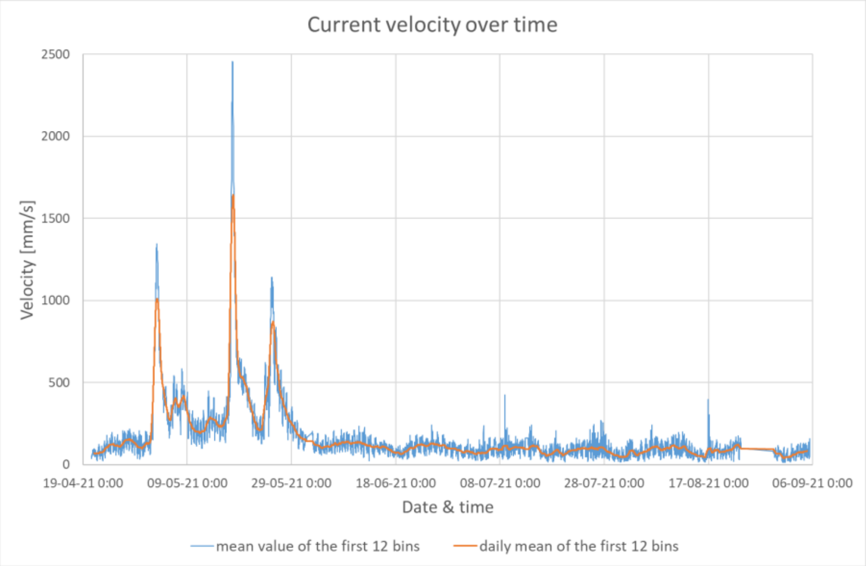


Figure 3-37 – The image shows the graph of the velocity of the current over time. Between the end of April and May there are 3 peaks which represent 3 flood events of the Isonzo river. The daily mean attenuates the fluctuations in current speeds due to the tide and possible other point factors upstream of the ADCP. The current velocity during flood events is approximately 20-30 times greater than the speed during low water periods.

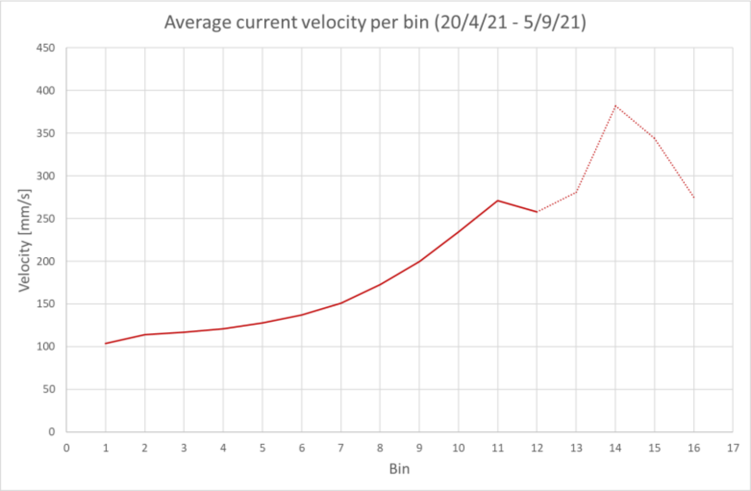


Figure 3-38- The graph describes the average speed of the current for each bin. The current velocity progressively increases from the bottom to the surface. The dotted line indicates the bins that are above the water surface.

3.4.3.3 Update of grain size data

In order to update the sedimentological data for the area, dating back to 1985 (Der. 3.2.2), a sampling campaign was carried out between October 2020 and January 2021 according to the sampling plan illustrated in derivable 3.2.2. Sediment sampling was conducted by Van Veen grab, position was determined through a GNSS Stonex S9III in NRTK mode. Per ogni bennata è stata prelevata una aliquota posta poi in sacchetti o barattoli etichettati con la propria sigla identificativa.

At the Laboratory of Sedimentology of the DMG of Università degli Studi di Trieste, the samples were sieved with a 63µm sieve to separate the sand fraction from the pelitic fraction; shell fragments were separated by sieving with a 1mm sieve. Samples were washed and treated with H^2O^2 to eliminate organic fraction and salt, then dried at 80°C for 24 hours. Grain size analyses were carried out using Malvern Laser Mastersizer 3000. The analysis operation yields the percentages of frequency of the various particle size classes, expressed in ϕ scale (corresponding to -log2 of the size classes in mm). The percentages of sand, silt and clay are used for sediment characterization according to the triangular diagram of Shepard (1954) and, finally, the distribution of particle size classes is described in terms of average diameter (Mz), sorting (SD), Skewness (Sk) and Kurtosis (Kg) according to ϕ notation, following Folk and Ward (1957).

Despite value differences due to different methods of grain size analysis, the new sedimentological data confirm the previous evidences of Brambati (Regione Autonoma Friuli Venezia Giulia, 1985) and the relationship between the geomorphology and the sedimentary dynamics of the area (Figure 3-39, Figure 3-40).

MZ (mean diameter) values were interpolated to create a sedimentological map (Figure 3-41) using an ArcGIS procedure: generation of a Triangulated Irregular Network supported by the addition of linear features as constraints, transformation into a GRID, and finally interpolation with the Kriging method available in the Geostatistical Analysis module.

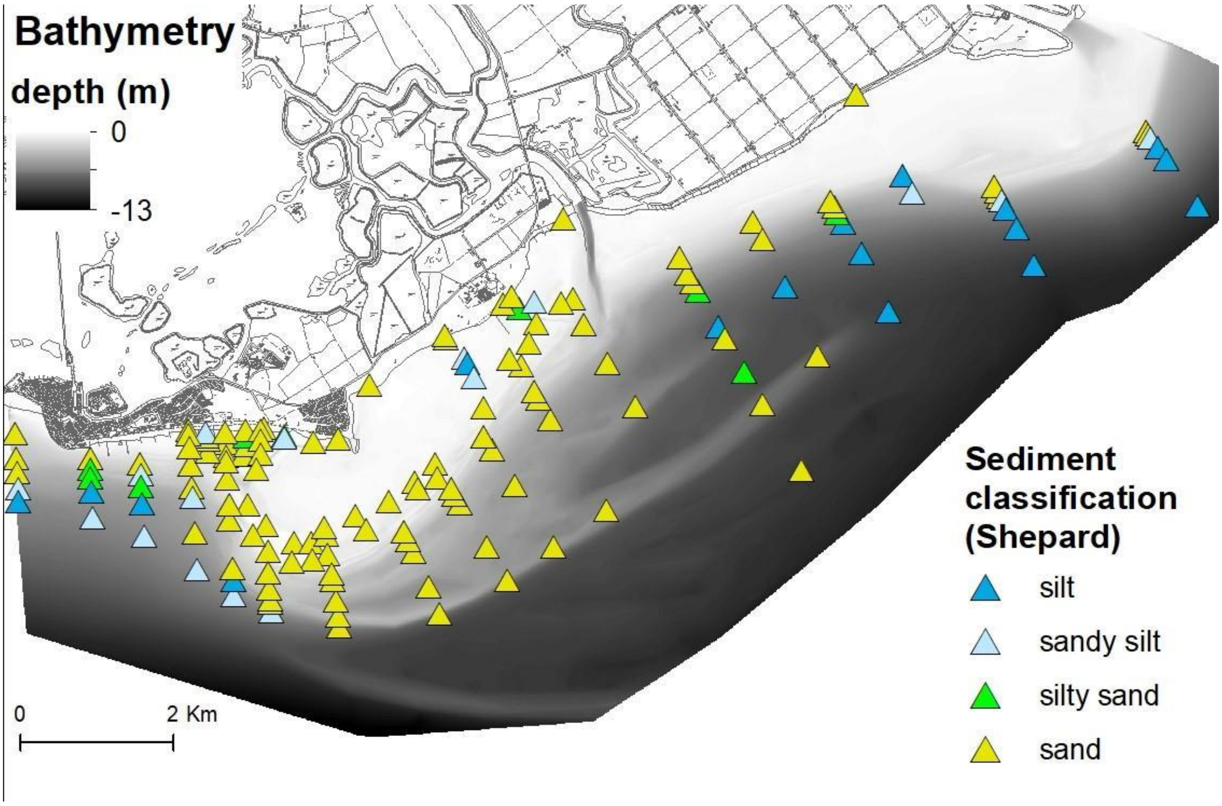


Figure 3-39 - Percent content of sand in the sediment samples (data 2019-2021): four classes are distinguished according to Shepard classification: sand (sand > 75 %, silty sand (50<sand<75%), sandy silt (25<sand<50%), silt (silt>75 %).

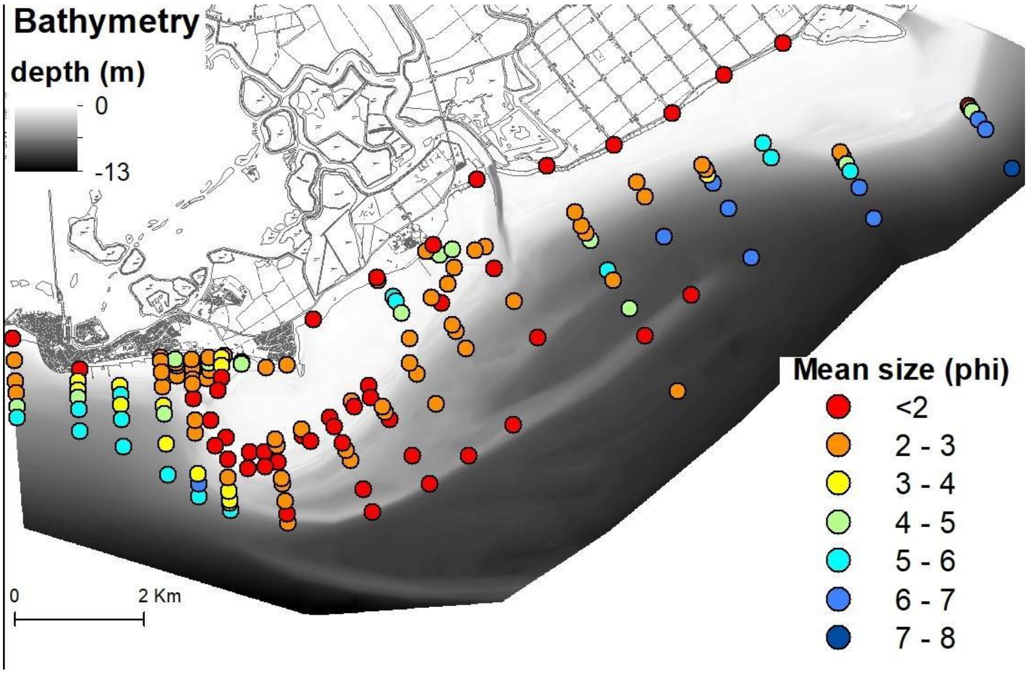


Figure 3-40 Distribution of mean size (phi) of the sediment samples (data 2019-2021): five classes are distinguished according to Wentworth classification: medium sand (1<MZ<2 phi, fine sand (2<MZ<3 phi), very fine sand (3<MZ<4 phi), coarse silt (4<MZ<5 phi), medium silt (5<MZ<6 phi), very fine silt (6<MZ<7 phi).

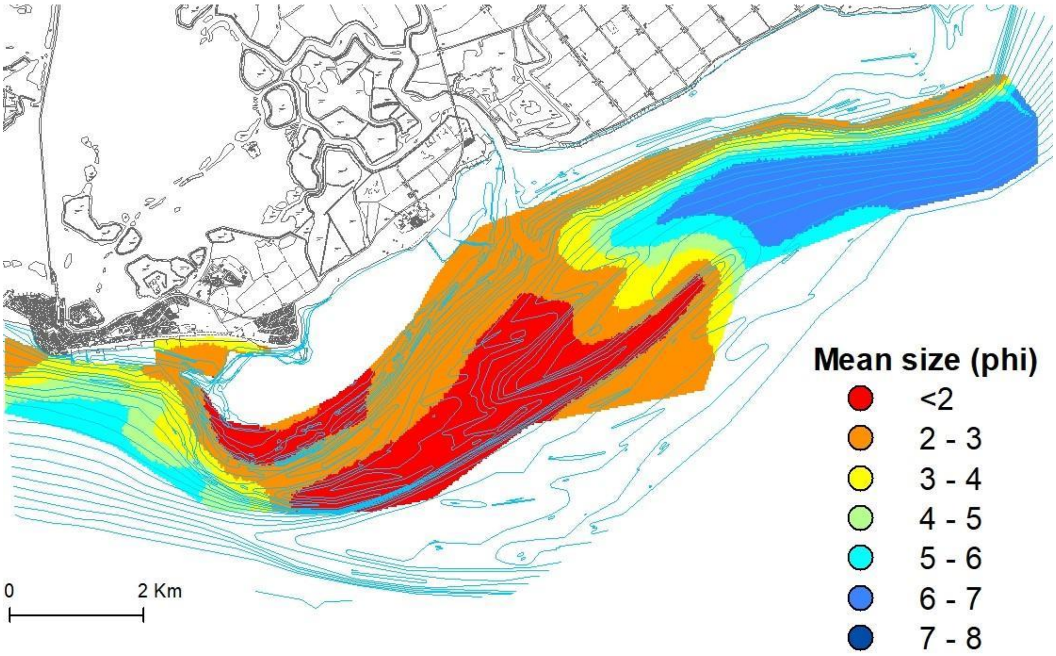


Figure 3-41 – Sedimentological map of the study area based on the most recent sampling (2020-2021)

3.4.3.4 Numerical modelling of hydrodynamics and morphodynamics

(with the contribution of R. Archetti, M.G. Gaeta, M. Mazzarella – Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum - Università di Bologna)

A morphodynamics and hydrodynamics study via numerical modelling was carried out by Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum - Università di Bologna. The first step of the study was the reconstruction of the meteo-marine climate, in particular starting from the analysis of previous marine meteorological investigations. Attention was focused on anemology climate, wave climate and also tides and sea water level variations. After reviewing the available material, a marine meteorological study was made based on the data provided by Friuli Venezia Giulia Region, recorded by wavemeter buoys located in the Gulf of Trieste (OGS).

The software used for the modelling was the MIKE by DHI and after preparing a detailed mesh and calculation grid, the two modules implemented were the Littoral drift (LITPACK) and the MIKE 21/3 coupled model.

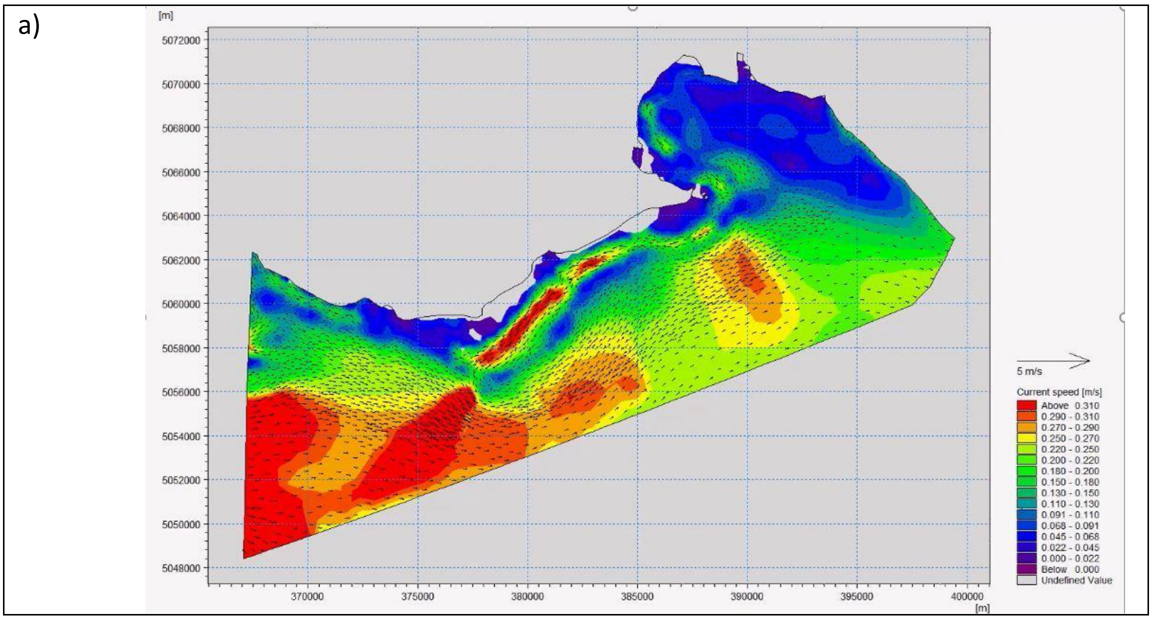
With the first one the trend of longshore solid transport along the coast profile was studied: a series of 10 profiles, up to -10m, normal to the shoreline were set and the transport was then calculated (Figure 3-42). Results confirm the prevalence of the longshore transport directed from east to west from Isonzo mouth to the Banco apex. Only the two most western profiles present a net longshore drift directed in opposite direction and this may explain how the lower rounded extremity of the Mula di Muggia has formed and maintained over years.

Figure 3-42 Representation of longshore transport for the entire area

The second module was the coupled idro-morphodynamic model, forced by wind, levels and also the river flow rate. For those simulations representative meteomarine conditions were identified, in particular there are events of storm (both of Bora and Scirocco), calm sea and also river flood. Results of those simulations showed how even during a Scirocco storm there is a dynamic by which currents and sediment transport coming from south direction rotates at the Isonzo outlet and proceeds on the Banco della Mula di Muggia in westward direction.

In conclusion another phenomenon occurring on the sand bank was partially analyzed: the formation of finger bars. Only a state of the art review was made with the description of the features of Banco della Mula di Muggia finger bars. Some hypothesis were proposed about the develop mechanisms, but certainly a deeper investigation with also the use of graphical and video imagery tools is highly suggested.

The results obtained through numerical modelling have recreated the morphology and hydrodynamics of the area in which the Banco della Mula di Muggia extends. The data collected from the results will certainly provide a starting point to carry out future further investigations, but also to be able to develop potential solutions to manage the sand accumulation that is leading to the formation of semi-marshy areas in beaches of tourist interest.



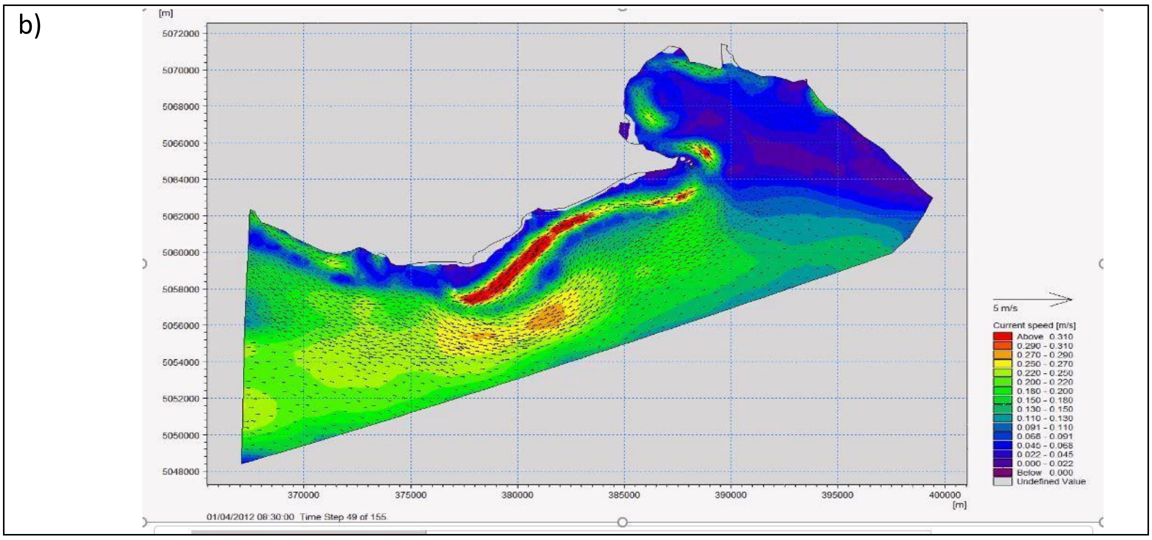


Figure 3-43 - Coupled model results: (a) Event 1 - Bora Storm Jan 26 to Feb 18 2012, (b) Event 2 - Scirocco Storm Mar 31 to Apr 10 2012

3.4.3.5 Morphodynamic simplified zonation and future perspective

The sedimentological, bathymetric and morphological data allow us identifying and mapping areas with different morpho-sedimentary characteristics, which can be considered as a basis for future management and planning (*Figure 3-44*).

- **Back-barrier area:** this area is characterized by shallow water and silting up, in prevalence of fine sediments, due to the shelter conditions against wave action.
- **Emerged sandy bank:** recent sandy accumulation areas, which is developing above mean sea level.
- **Sandy accumulation area**: bar and trough zone with strong sandy accumulation.
- **Longshore migrating sandy bars**: includes the sandy bar and trough zone where the sedimentary budget is substantially balanced. Morphological evidence testifies a strong longshore transport from east to west.
- **External area**: from the bank outer limit to the closure depth within the range -2 -2.5 m and -5.4 m it appears interested both by accumulation and erosion processes. Morphological features suggest that the transport is directed towards N-E, that is, opposite to the direction of migration of the Banco.
- **Nourished beach**: touristic beach which needs periodically nourishment interventions.
- **Open beach**: sandy beach expose to wave action.
- **Protected beach:** sandy beach protected against wave action.

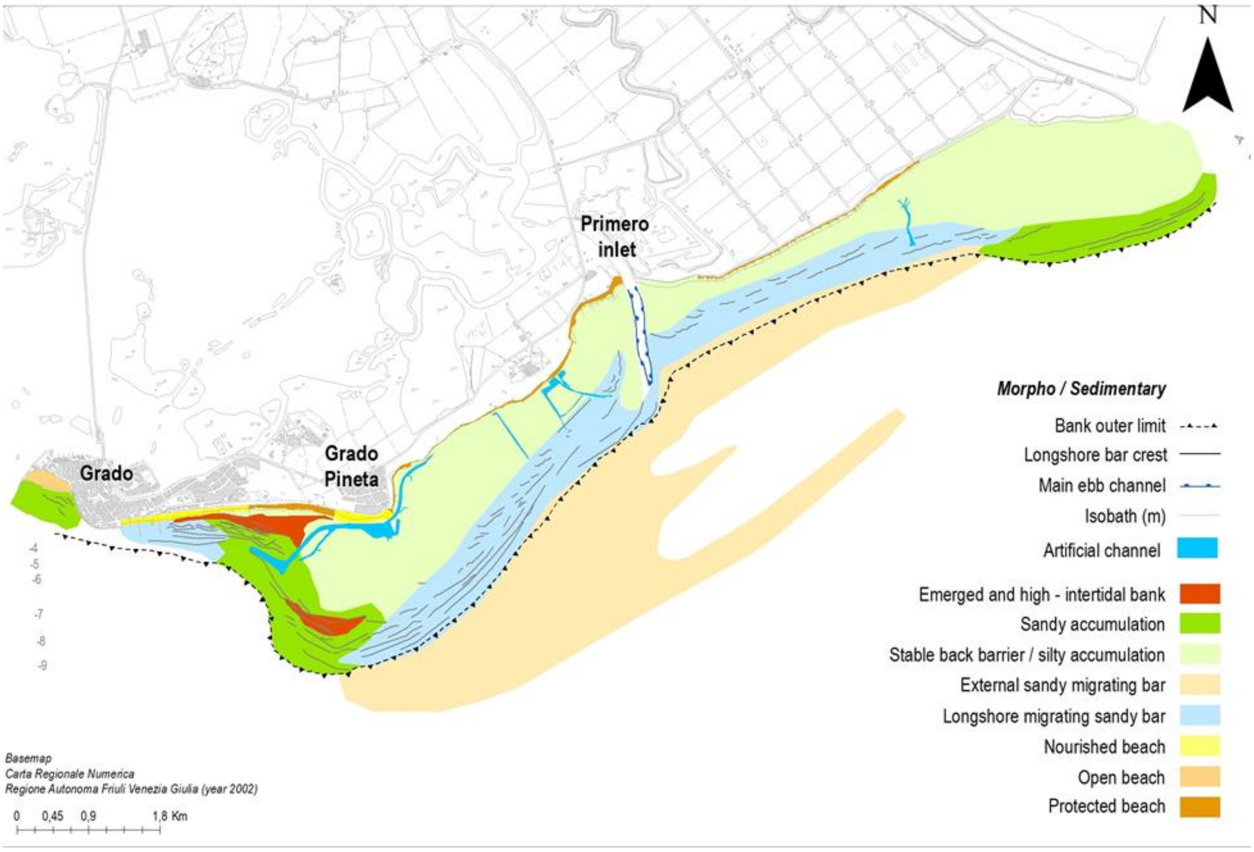


Figure 3-44 Simplified morpho-dynamics representation of areas with different characteristics in the pilot site.

Finally, the data allow some considerations about the future morphological evolution of the area. Comparing the sedimentation rates obtained for our computation in the area of the Banco della Mula di Muggia (average rate in the interval profile P3-P8 = +5.8mm/y for 1968-2019, +5.3mm/y for 1985-2019 and +7.4mm/y for 2007-2019), with the rate of sea level rise presented in *Table 1*, the sea transgression effect and the sedimentary accumulation are resulting almost balanced for the scenario RCP2,6. In the area of the maximum accumulation of the Banco, depositional rates exceed the sea level rise rate by at least twice as much: it is probable that depositional areas will maintain in the future, even considering the maintenance or increase of sea-level rise rates. The future entity of the westward migration of the bank, which represent an important issue for the touristic use of the beaches, is difficult to predict. A simply trend projection will indicate a migration of about 1000m to the year 2100. The longshore transport corridor present a deficit of sediments if compared to the sea level rise and tend to deepen: a probably morphological response could be a landward shifting of the bar and troughs area. In this case the sand banks could shrink or could be tightened as consequence of a typical roll-over process.

The Isonzo delta lobe exhibits signs of active deposition, which may indicate that the river's sediment supply is maintained, but this cannot be confirmed due to a lack of data on the river's solid discharge.

The most significant issue to assess the coastal sector's ability to mitigate sea level rise and the resulting transgression processes is the river's effective solid discharge and its trend in the coming years and decades.

The long term changes of river flows are expected in the Adriatic region as a result of the combined effects of climate changes in the Mediterranean and human usage of freshwater (Alcamo et al., 2007). The increase of air temperature (1–5.5 1C) and a decrease of the overall precipitation (35–40%), mainly from June to August, might lead to a significant reduction of the duration of snow cover and a reduction of 30–70% of the extent of the largest alpine glaciers, with an increase by 60–140 m/°C in altitude of their snow line. River flows are expected to increase during the earlier phase of glacier melting and to strongly decrease afterwards, a condition that might exacerbate the water stress due to the anthropogenic usage. Although model results are still largely uncertain, they suggest decreases of the river runoff in the North Adriatic area from 5 to 50% (Cozzi & Giani, 2011).

The flow dynamics at the river mouths does not reflect only the natural pluvio-nival conditions. Human interventions addressed to freshwater management, mostly occurred until the 1960s, have deeply modified drainage networks and lake systems through the massive building of channels, dams and embankments. For this reason, a general decline of runoff is taking place in the North Adriatic, in particular since the last decade (Cozzi & Giani, 2011).

In contrast, we must consider the increase in extreme events and hence in floods, which are responsible for much erosion and solid transport.

In this frame, specific data on the Isonzo River are limited. The most recent data of max monthly level of the Isonzo (Gorizia Hydrometer 1999-2017) show a slowly positive trend, despite the signal of climate change on the rainfall of Friuli Venezia Giulia is not clear, also due to the strong interannual variability of this meteorological quantity (Fontolan et al., 2015).

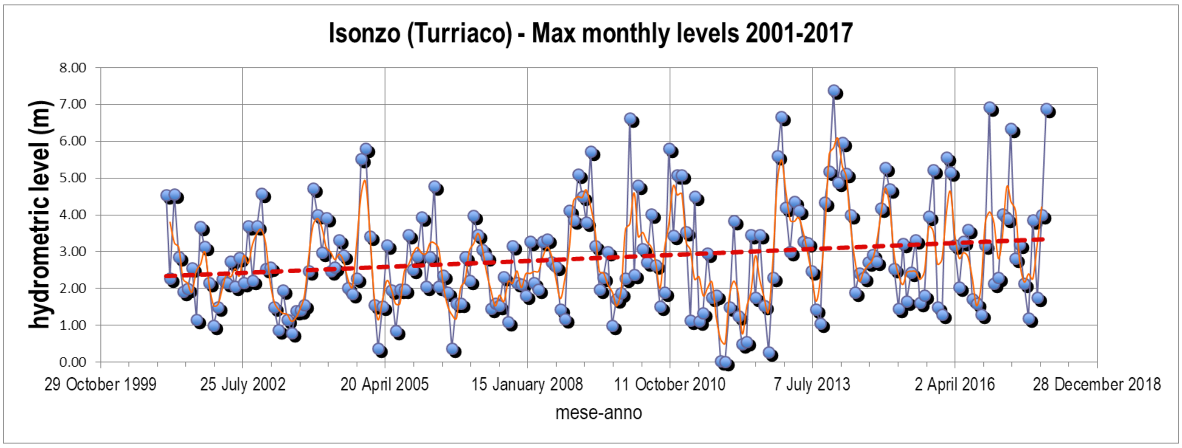


Figure 3-45 Recent slow positive trend of the hydrometric level measured on the Isonzo River (Turriaco station)

3.4.4 Short term and long term vulnerability

This section will present a short- and long-term estimate of coastal vulnerability in the Grado municipality, with an emphasis on the coastal tract between Grado and the Primero inlet.

3.4.4.1 Short-term vulnerability

Flooding is generally considered the most risky event in coastal area management. Flooding can be defined as a *temporary marine transgression affecting coastal areas*, *with short timescales, in a well-defined area*. Among the causes can be identified some natural phenomena, such as storms, generally associated with exceptional high tide events, or high water ("acqua alta"). The phenomena of high water ("acqua alta"), which is of relevance to the Northen Adriatic, is caused by the combination of a high spring tide, low atmospheric pressure, and a strong continuous wind, which generates a seiche along the north-Adriatic coast (frequently the Scirocco wind, but also in conditions of Bora).

The altimetry of the coastal land has a strong influence on the distribution of hazard zones in terms of flooding. The most recent data for the study area is from 2018 (Lidar data provided by the Protezione Civile Friuli Venezia Giulia, Figure 3-46).

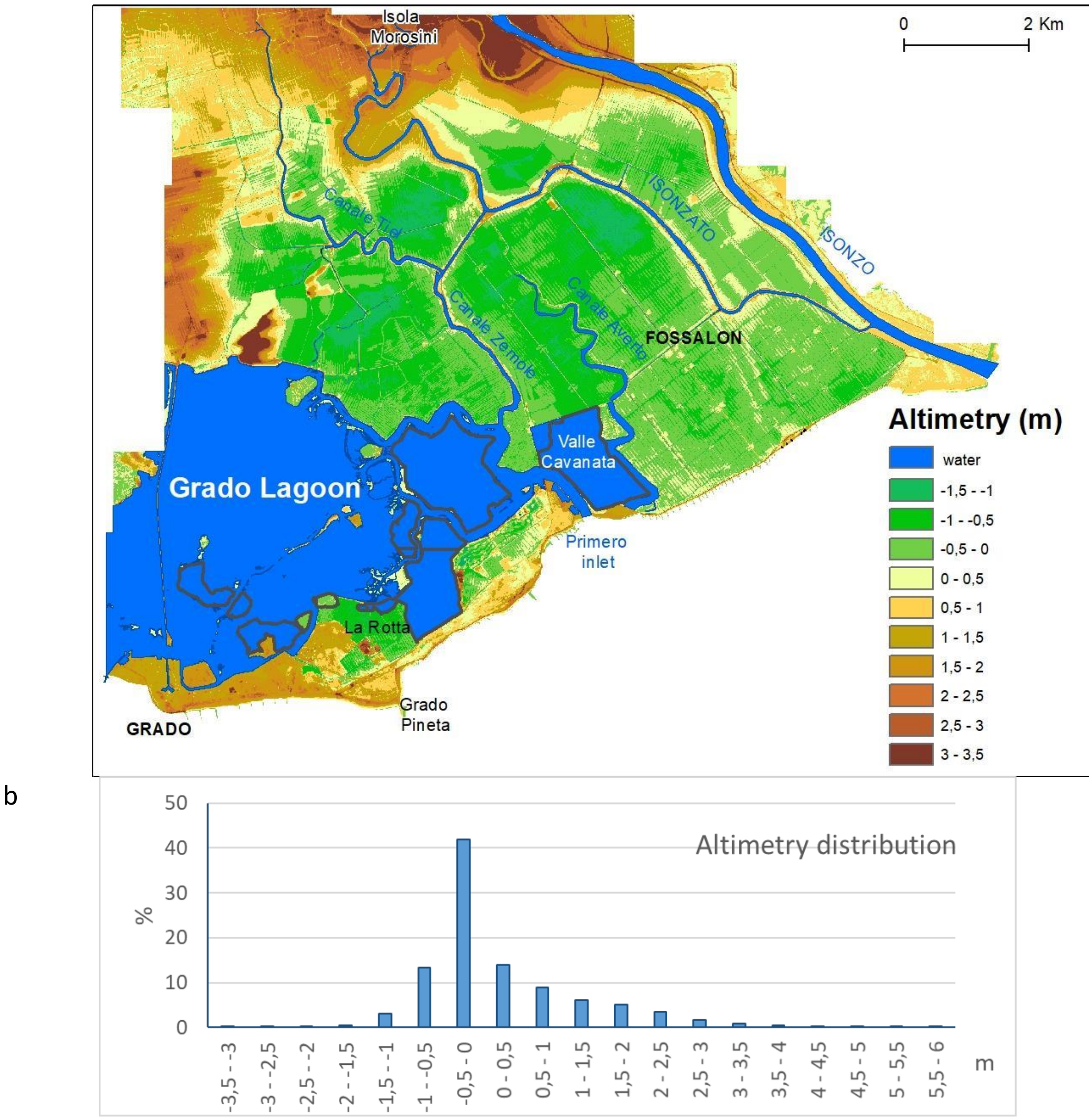


Figure 3-46 – (a) Digital Terrain Model from 2018 for the municipality of Grado, (b) Altimetry distribution of the Grado area based on the most recent data (Lidar 2018 by Protezione Civile Friuli Venezia Giulia).

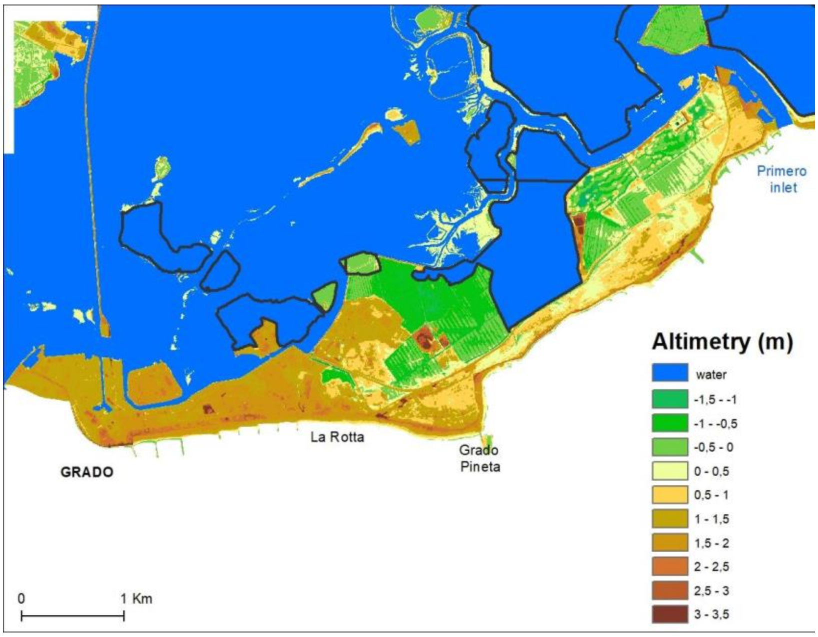


Figure 3-47 - DTM from 2018 for the coastal tract from Grado to Primero inlet

As seen in the figures, the majority of the land lies below mean sea level (about 8000 ha, or 50% of the total), with values ranging from -1.5 to -2 m. Diffuse artificial hydraulic drainage has produced these low-lying areas, which are sheltered from the sea by hard coastal defences. A narrow coastal strip is the only land above mean sea level, reaching maximum heights of 3-3,5m as relics of previous coastal morphologies (dunes and beach ridges) (Figure 3-47).

In case of overcoming of the embankments, these lowlands would be submerged by simple transfer of water from the lagoon or from the canals. Once flooded, these areas are extremely difficult to drain and overflow waters may persist for several weeks.

The risk associated with marine ingression for this area has already been highlighted by Marocco and Pessina (1995), who showed a high vulnerability for all the areas bordering the lagoon, also following the disastrous event of November 1966, when a concomitance of flood and storm surge occurred with important damages in the region (Figure 3-48). After that event, embankments were built for the defence of the territories bordering the sea up to the +3.00m, with a concrete wall on the pre-existing in earth and with stones on the foot.

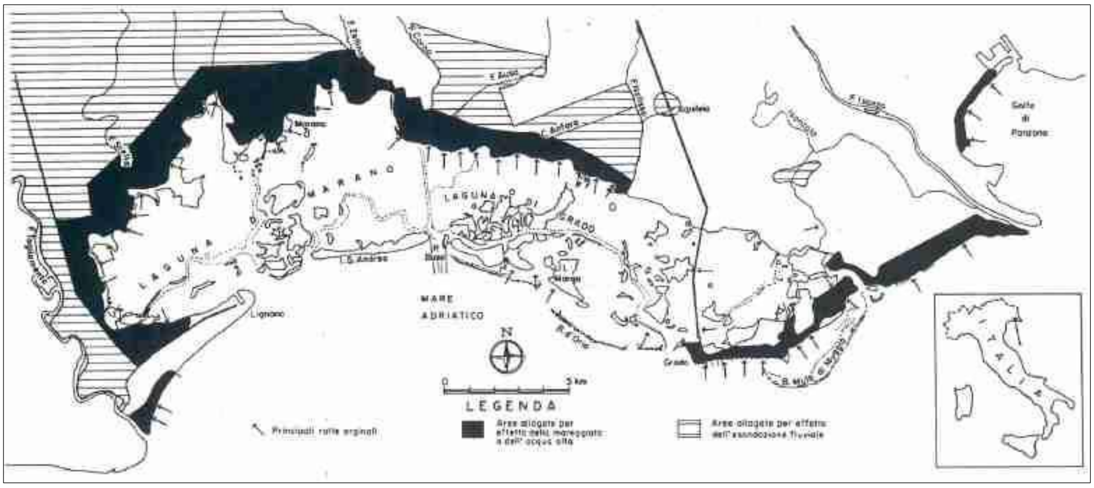
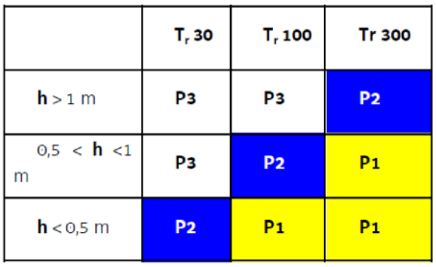


Figure 3-48 – Main embankment breaches and flooded areas during the event of November 1966 (from Marocco & Pessina, 1995), black zone = areas flooded by storm surge, striped white zone = areas flooded by the rivers.

A recent assessment of the hydraulic hazard of the Grado area is presented in the report *Piano stralcio per l'Assetto Idrogeologico regionale (PAIR) dei bacini idrografici dei tributari della laguna di Marano – Grado*.

Based on the provisions of the Floods Directive and D.L. 49/2010, three classes have been identified: P1 (low hydraulic hazard), P2 (medium hydraulic hazard) and P3 (high hydraulic hazard) (Figure 3-49; Figure 3-50). The hydraulic hazard is represented by the potential marine ingression and by the riverine flooding (class F), the last limited to the area of the mouth of the Isonzo. Most of the area identified in the map as P3 are fish farms. For the determination of hazard classes, it was considered the crossing of the water level achieved (h=hydraulic head separated into three classes 0-0,5 m, 0,5-1 m, >1 m) with the varied likelihood of occurrence (T1, T2, T3 Table 4 (b) is considered for the estimation of hazard classes (a).



	Tr 30	Tr 100	Tr 300
h > 1 m	P3	P3	🟦 P2
0,5 < **h** <1 m	P3	🟦 P2	🟨 P1
h < 0,5 m	🟦 P2	🟨 P1	🟨 P1

a

T (years)	Level (m)	Set-up (m)	Total level (m)
30	1,4	0,2	1,6
100	1,6	0,4	2,0
300	2,0	0,4	2,4

b

Table 4 Estimation of hazard classes.

The method is based on the analysis of a Digital Terrain Model (DTM from LIDAR data from 2008), referring to the possible levels reached by the sea and the application of a corrective factor, based on the distance from the shoreline, to account for the loss of water load during a marine flood event.

The maximum level of high water (H_t) that may affect the area with the different probability of occurrence (T) has been evaluated by performing a statistical analysis of the experimental data recorded at the tide gauge of Trieste (available data since 1875) distinguishing the following components:

$H_t = L_{ms} + H_{astr} + H_{surge} + H_s + S_{up}$

where H_t= total level, L_{mm} = mean sea level, H_{astr} = astronomical tide, H_{surge} = surge height, H_s = seiche high, S_{up} = wave set-up.

The set-up is considered only for normally decreasing seabed not protected by external coastal barriers or shoals.

For each of the considered scenarios, this type of methodology has enabled for the identification of potentially floodable areas of the coastal strip. The analysis of the altimetry terrain distribution allowed for the identification of morphologically depressed areas with "openings" that allow seawater intrusion, thereby rejecting the “isolated” areas that would not be affected by floods. According to the Plan, *all the altitudes inferior to 3 m and still more those inferior to 2,5 m or to the 2 m, must be considered critical until extremely critical, that is, susceptible to overflows in exceptional occasions of high waters, therefore liable to generate flooding in the immediate hinterland*. For this reason the Plan prescribes the height of +3,00 m above sea level for all the coastal embankments.

Figure 3-49 Areas considered at different hydraulic hazard in the pilot site area (from PAIR).

Figure 3-50 - Areas considered at different hydraulic hazard in the pilot site area (from PAIR)

For the beaches, the PAIR does not define any class of hazard. The areas behind the beaches, landward of the protection structures (embankments or walls), are almost constantly classified as zone of moderate danger P1, with the exception of some sectors with P2 zones. The possibility of river flooding is limited to the course of the river Isonzo that could involve the area of Fossalon limited to the area of the mouth. To complete the analysis of the PAIR, a coastal vulnerability analysis has been applied here, which is inspired by the Coastal Vulnerability Index (CVI) developed by Gornitz et al., 1994. The methodology of Gornitz et al. (1994) is one of the most commonly used and is a simple method to assess coastal vulnerability to sea level rise, in particular due to erosion and/or inundation. It was modified and used for example for the coasts of Veneto (Fontolan et al., 2011). The method is based on the principle that vulnerability to flooding is strongly conditioned by the geomorphological and sedimentary characteristics of the coastal sector, which determine the ability or not to dissipate wave energy.

The *potential vulnerability* is defined as a linear combination of morphological and evolution variables, which measure the natural susceptibility of the coastal regions to the erosion and overstepping. The presence of natural and rigid protections leads to a reduction of the potential vulnerability, resulting in what it is called real vulnerability.

The first step for the calculation of the potential vulnerability deals with the identification of key variables representing significant driving processes influencing the coastal vulnerability and the coastal evolution in general. The second step deals with the quantification of the identified key variables, generally based on the definition of semi-quantitative scores; afterwards (third step) key variables are aggregated in a single index, through the formula:

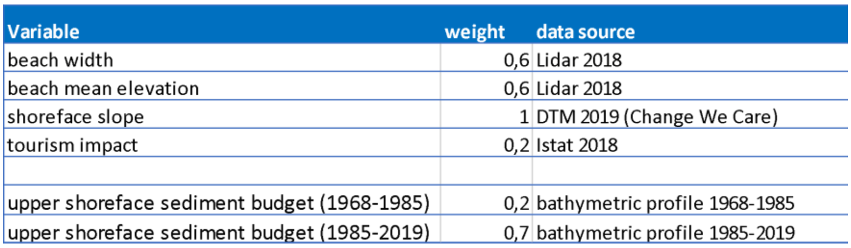
$CVI = v_1k_1+v_2k_2+v_3k_3+.....+v_nk_n$ where v = variable value, k = variable weight.

In our case, the selected variables are listed in the Table 4, where also the assigned weights are presented.

The shoreline has been partitioned into segments with similar characteristics (Figure 3-51 and Figure 3-52). Each variable's value has been obtained from the most recent available data for each sector (Table 6). Each variable was converted to a scale of 0 to 4, with 0 corresponding to the lowest vulnerability class and 4 corresponding to the highest vulnerability class. The normalization has been carried out by using a linear interpolation of the measured values, assuming that the coastal susceptibility to erosion increases for low values of some morphological parameters, such as width and height of the beach, while it decreases for higher value of such variables. The "worst" and "best" morphological conditions were based on data collected throughout the North Adriatic Sea to produce results comparable to other sites (e.g. Delta Po, Bezzi et al. 2021). As indicated in the Table 4 aerial photointerpretation and DTMs were employed for the evaluation of the morphometric parameters of the identified units (mean width of the beach, average beach elevation, shoreface slope, upper-shoreface volume change) and for the estimation of their multi-decadal evolution.

We opted not to utilize some common variables in the CVI calculation in the instance of the Grado coastal area, such as the shoreline evolution trend (recent and historical). The reason of excluding the shoreline trend is the peculiar morphodynamic characteristics of the Grado beaches. In most part of the littoral (from sector GF to FD) the beaches can be considered as fetch-limited environments because they are protected from sea-generated waves by the bar system of the Banco della Mula di Muggia. Here the sandy beaches are artificially nourished or can be considered as relict morphologies. In the other cases (GC and GD) sandy beaches are very strongly influenced by frequent coastal works and the recent shoreline evolution can't be considered as a suitable indicator of the dynamical behavior of the area.

The data for each variable are presented in Table 6 and in the graph of Figure 3 53, together with the resulting values of the Coastal Vulnerability Index: the most vulnerable beaches resulting in the fetch limited – area, where the scarce beach width and elevation are determinant.



Variable	weight	data source
beach width	0,6	Lidar 2018
beach mean elevation	0,6	Lidar 2018
shoreface slope	1	DTM 2019 (Change We Care)
tourism impact	0,2	Istat 2018
upper shoreface sediment budget (1968-1985)	0,2	bathymetric profile 1968-1985
upper shoreface sediment budget (1985-2019)	0,7	bathymetric profile 1985-2019

Table 5 – Variables with assigned weight and data source

Figure 3-51 - Identified cells along the Grado coast (from Grado to the Primero inlet)

Figure 3-52 - Identified cells along the Grado coast (from the Primero inlet to the Isonzo mouth).

Table 6 – Variable values for each cell.

Tract	Lenght (m)	Beach width (m)	mean beach elevation (m)	Uper shoreface slope (0-5m)	Tourism impact	Shoreface budget (mc/m/year) 1968-1985	Shoreface budget (mc/m/year) 1985-2019
GA	672	155.2	1.4	0.0050	253	14.11	2.76
GB	856	0	--	0.0080	0	-16.65	2.87
GC	853	79.5	1.4	0.0067	253	-10.64	14.37
GD	776	67.8	1.3	0.0048	253	-4.64	20.55
GE	697.9	53.7	1.3	0.0029	203	82.67	63.24
GF	375	77.1	1.3	0.0022	152	82.67	33.28
GG	756	98.8	1.4	0.0022	253	9.09	0.42
GH	560	19.0	0.6	0.0023	0	0.37	-2.24
GI	1902	11.1	1.0	0.0022	25	-10.90	-0.36
GL	2063	35.5	1.3	0.0030	152	-0.26	2.48
FA	782	0.0	--	0.0047	0	-4.33	3.82
FB	2244	18.3	1.4	0.0047	0	4.36	2.01
FC	984	23.4	1.3	0.0038	25	0.83	7.95
FD	1263	9.1	--	0.0024	0	-7.43	31.33
FE	583	570	--	0.0024	0	11.40	43.53

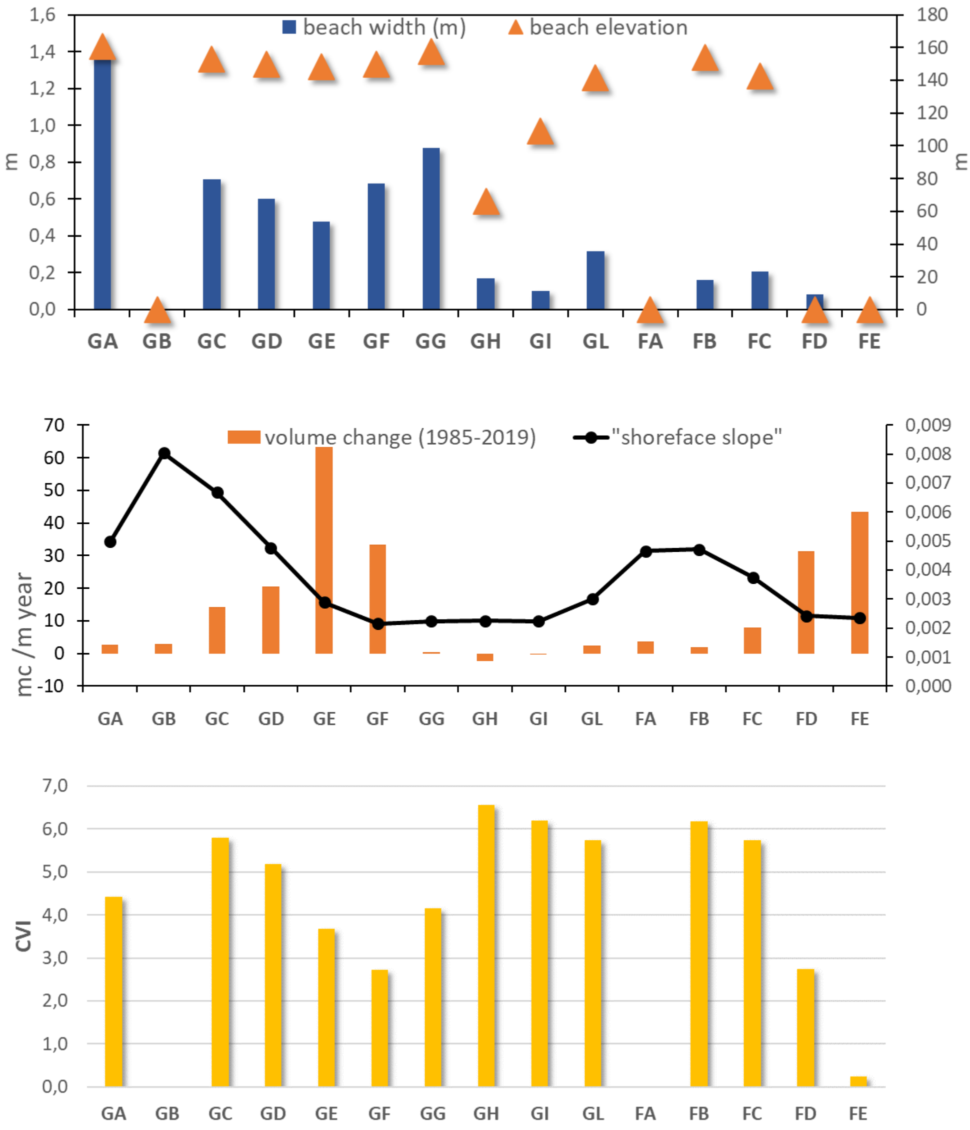
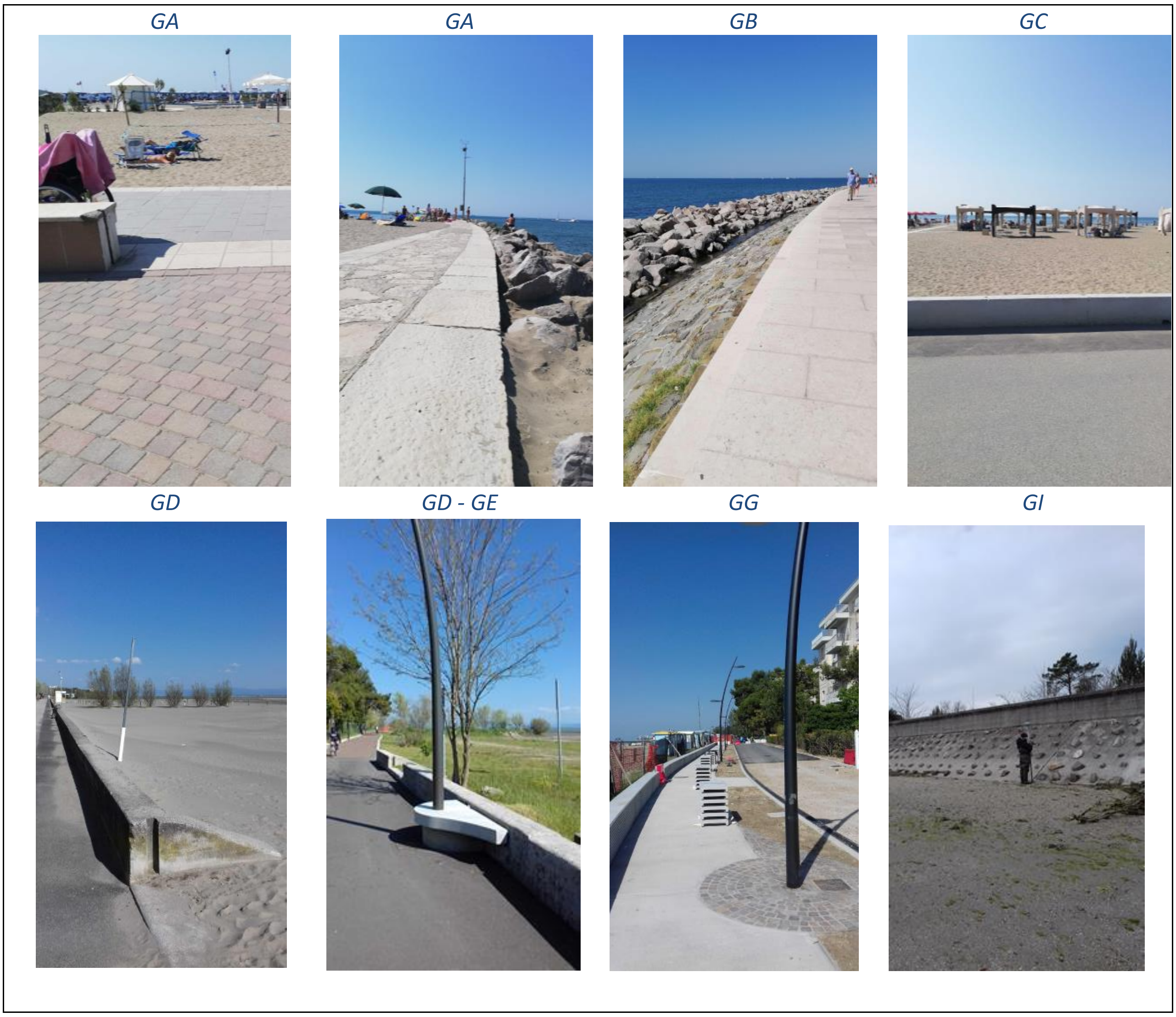


Figure 3-53 Variable values and resulting CVI for each cell.

Dunes and defence structures can reduce the potential vulnerability by offering reinforcement to the coast and protecting the land against potential flooding by storm waves and surge. The real vulnerability is thus computed by subtracting the contribution of each element defending the coast from the potential vulnerability. Several parameters contribute to define the efficacy of these elements and reducing vulnerability. Similarly, the contribution of rigid protection depends on their characteristics, such as location (sea protection, longshore protection, inland protection) and elevation above the mean sea level. In the Table 7 and Figure 3-54 the coastal defences of the Grado area are summarized.

	Dunes and earth embankments	Elevation (m)	Efficacy	Hard defences	Elevation (m)
GA	--	--	--	wall in the back beach	2,44
GB	--	--	--	seawall	3,63
GC	--	--	--	wall in the back beach	2,31
GD	--	--	--	wall in the back beach	2,22
GE	--	--	--	wall in the back beach	2,40
GF	relict dunes	2,54	0,6		
GG	--	--	--	wall in the back beach	2,7
GH	embankment	2,27	--		
GI	--			K embankment	3,4
GL	--			K embankment	3,3
FA	--	--	--		
FB	--	--	--	K embankment	3,1
FC	foredune	2,7	0,6	K embankment	3,1
FD	--	--	--	K embankment	3,0
FE	--			K embankment	3,0

Table 7 - Coastal defences in the coastal tracts



GA GA GB GC

GD GD - GE GG GI

Figure 3-54 - Coastal defences in the study area

3.4.5 Long -term vulnerability

A series of flooding-sea maps was created using the different sea level from Table 3 on the DTM (Digital Terrain Model) to produce a high resolution model of the coastal territory under different scenarios of relative sea level rise that could be expected in 2100. The maps report the areas below sea level that are not inundated and areas that are permanently flooded because they are next to the sea or the lagoon or are directly related to a probable water penetration pathway for each scenario.

The first test uses the RCP 2.6 minimum scenario with a 0.29 m relative sea level increase. Within this scenario, the area below the mean sea level goes from 7686 (today mean sea level) to 9084 hectares. Only part of the beaches and saltmarshes in the Grado lagoon are resulting as permanently flooded (total area of 65 ha).

About the saltmarshes, it is necessary to consider their capability to naturally counteract the sea level rise. Saltmarshes occupy a narrow elevation range in the intertidal domain and respond to sea level rise through a series of complex and dynamic bio-physical feedbacks. The vegetation changes enhance the saltmarsh resilience, favoring sediment trapping and silting up with increase of elevation. Saltmarshes persist in their current locations only if they can continue to build vertically at a rate equal to or greater than the rate of sea level rise.

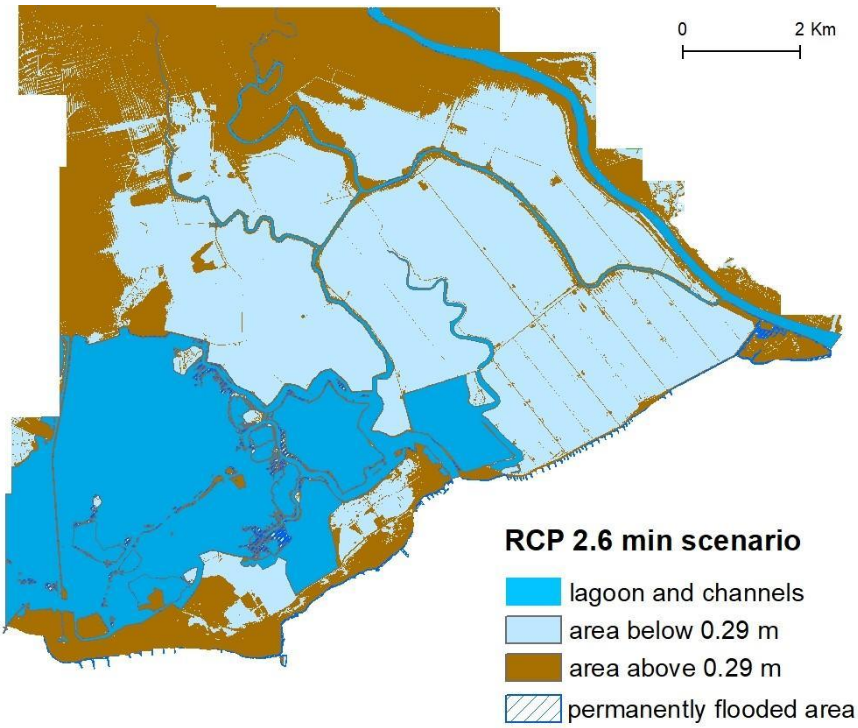


Figure 3-55 - The coastal territory of Grado under RCP 2.6 minimum scenario (+0.29m).

Considering the RCP 2.6 average scenario (+0.43 m) and the RCP 2.6 maximum scenario (+0.59 m) the permanently flooded areas are 90 and 209 ha respectively (the 0.6 and 1.4 % of the investigated area) and are represented by beaches, saltmarshes and floodplains. The territory below the mean sea level is resulting in 9600 ha and 10316 ha respectively (Figure 3-56, Figure 3-57). The increase of flooded areas under the RCP 2.6 maximum scenario is due to a large floodplain on the Isonzo western side.

Then, we only simulated the RCP 8.5 average scenario (+0.84 m) because the expected RSLR within the RCP 8.5 minimum is close to the RCP 2.6 maximum scenario. The flooding map for the RCP 8.5 average shows an increase in the area under sea level to 11253 ha and the permanent flooded area to 253 ha

(Figure 3-58). Finally, the RCP 8.5 maximum scenario with a relative sea level rise of 1.1 m determines an area of 11908 ha below the mean sea level and a permanently flooded area of 289 ha (Figure 3-59).

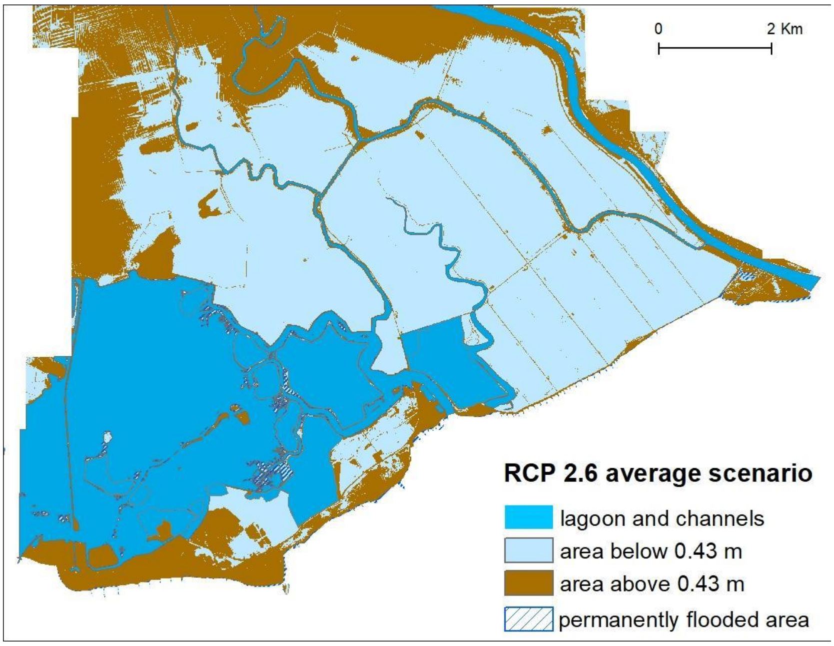


Figure 3-56 - The coastal territory of Grado under RCP 2.6 average scenario (+0.43m).

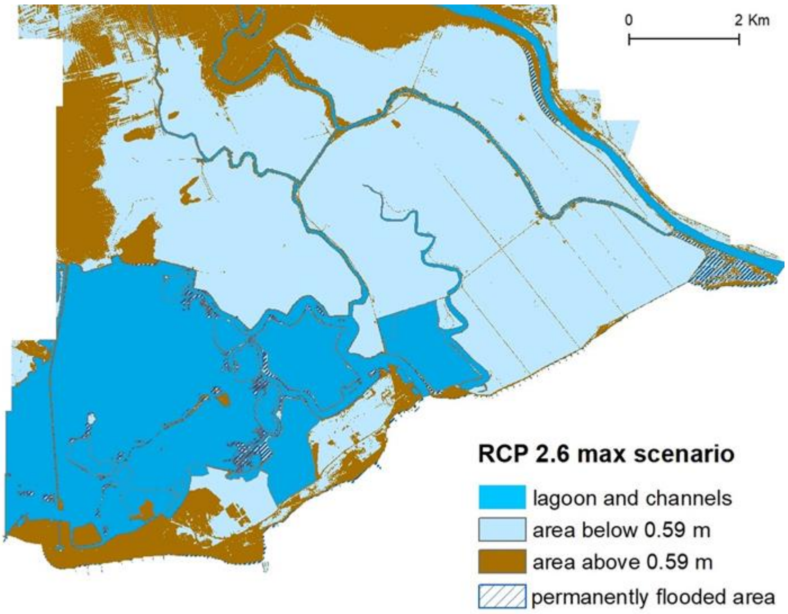


Figure 3-57 - The coastal territory of Grado under the RCP 2.6 maximum scenario (+0.59m)

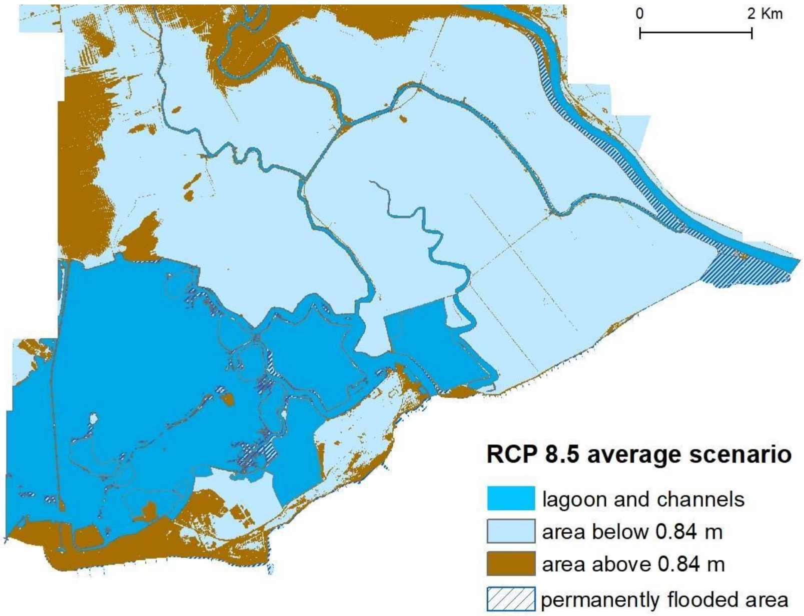


Figure 3-58 - The coastal territory of Grado under the RCP 8.5 average scenario (+0.84).

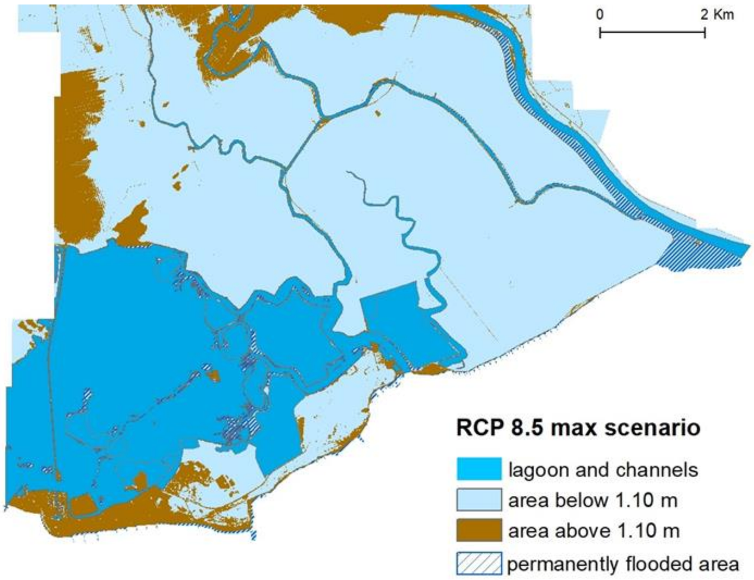


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Figure 3-59 - The coastal territory of Grado under the RCP 8.5 maximum scenario (+1.10 m).

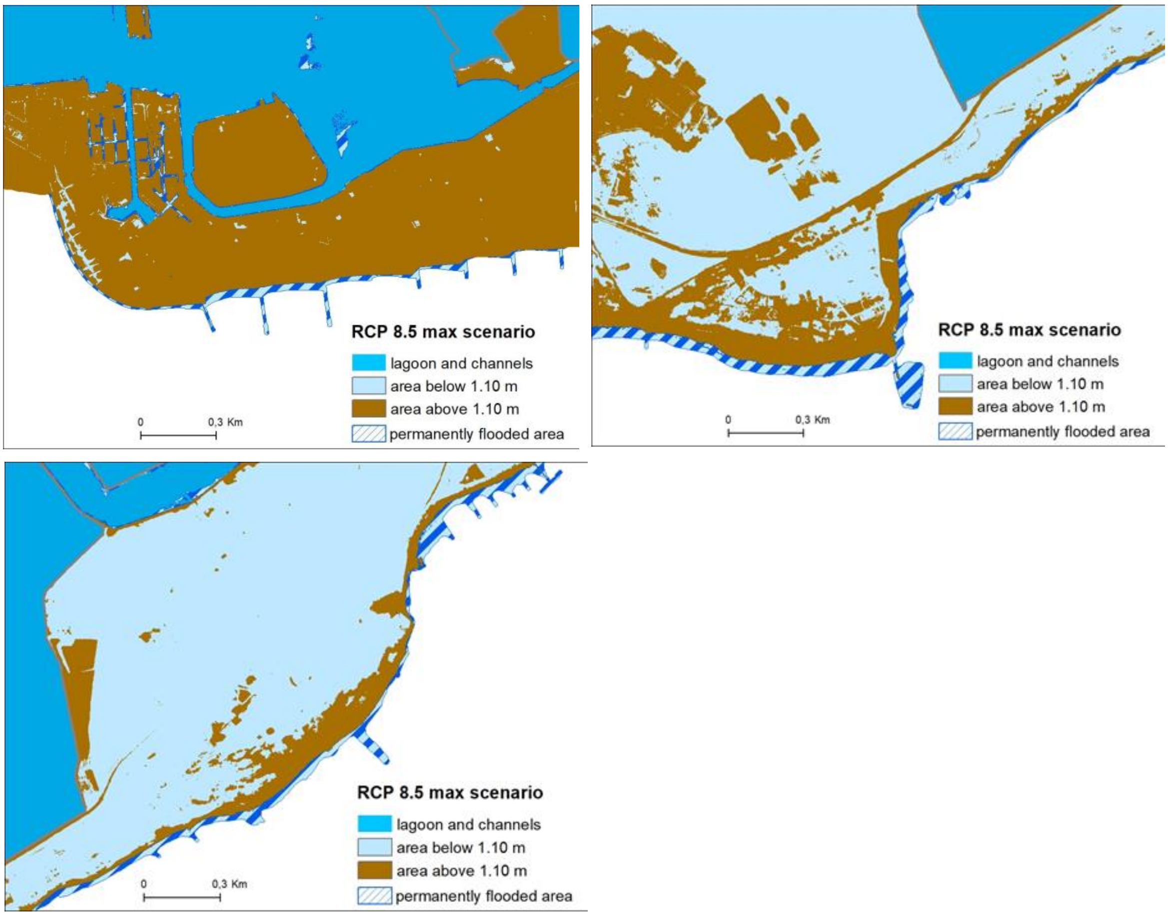


Figure 3-60 – Some tracts of the coastal territory of Grado under the RCP 8.5 maximum scenario.

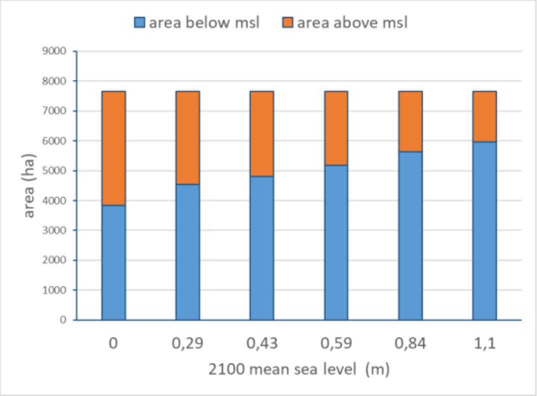


Figure 3-61 – Distribution of the area below and above sea mean level according to the analyzed 2100 scenario.

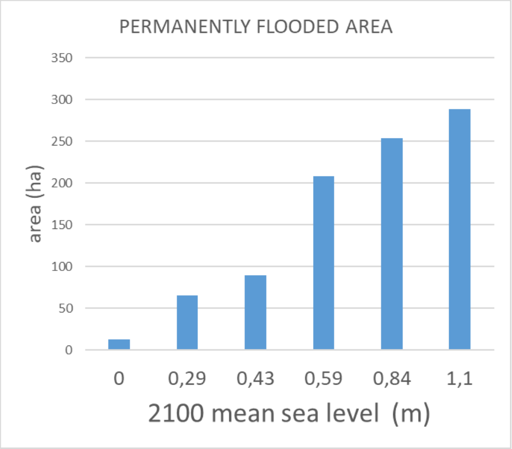


Figure 3-62 - Distribution of permanently flooded areas according to the analyzed 2100 scenario.

With the same method we also evaluate the effect of high water in a recurrence time of 30 years (as defined in Tab. 4b) applied to the RCP 2.6 minimum RSLR scenario (1,40 + 0,29 = 1,69cm). In this scenario the beaches are completely flooded but there are no points of water penetration from the sea inland, while the lagoon edge of the town of Grado is the most critical element (Figure 3-63).

Finally, applying the effect of the storm surge to the scenario RCP 2.6 maximum we get the map of Figure 3-64. Here the risk areas are approximately unchanged but the first points of probable water penetration are highlighted also in the back- beach, in particular at the Spiaggia Azzurra of Grado, on the eastern sides of Grado Pineta and at the mouth of Primero. Also the probability of water penetration on the inner shores of the lagoon increase significantly.

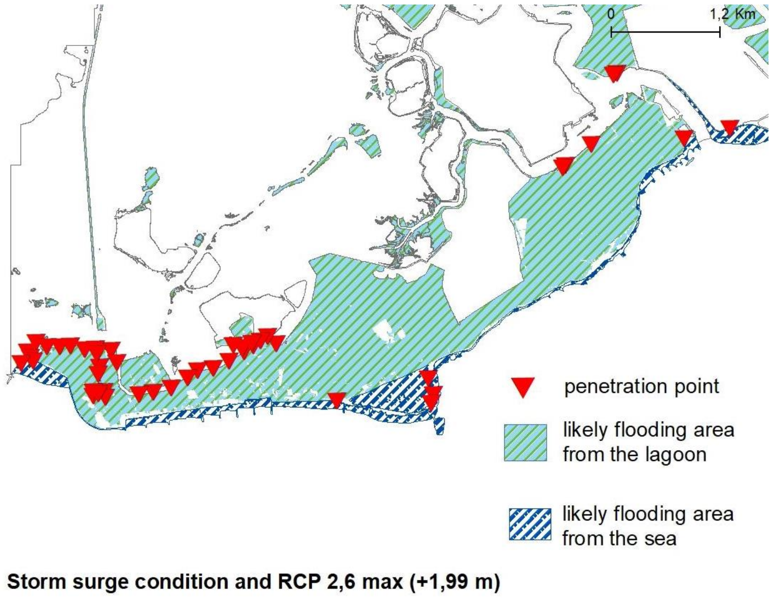


Figure 3-63 - The territory of Grado under the RCP 2.6 minimum scenario in high water condition (+1.69 m). Areas of different color are at risk of flooding due to the presence of likely points of water penetration.

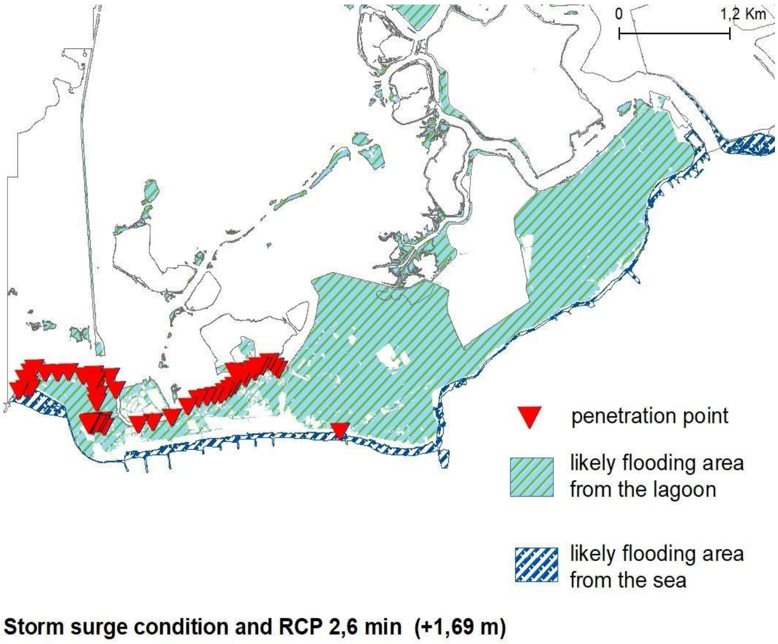


Figure 3-64 The territory of Grado under the RCP 2.6 maximum scenario in high water condition (+1.99m). Areas of different color are at risk of flooding due to the presence of likely points of water penetration.

3.4.6 References

- Alcamo, J., Moreno, J.M., Nova´ ky, B., Bindi, M., Corobov, R., Devoy, R.J.N., Giannakopoulos, C., Martin, E., Olesen, J.E., Shvidenko, A., 2007. Europe. in: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E.(Eds.), 2007. Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK, pp. 541–580.
- Antonioli, F., Anzidei, M., Amorosi, A., Lo Presti, V., Mastronuzzi, G., Deiana, G., De Falco, G., Fontana, A., Fontolan, G., Lisco, S., Marsico A., Moretti M., Orrù P.E., Sannino G.M., Serpelloni E., Vecchio A., 2017. Sea-level rise and potential drowning of the Italian coastal plains: Flooding risk scenarios for 2100, Quaternary Science Reviews, 158, 29–43, doi:10.1016/j.quascirev.2016.12.021.
- Anzidei, M., Bosman, A., Carluccio, R., Casalbore, D., D'Ajello Caracciolo, F., Esposito, A., Casalbore D., Nicolosi I., Pietrantonio G., Vecchio A., Carmisciano C., Chiappini M.., Chiocci F. L., Muccini F., Sepe V., 2017. Flooding scenarios in coastal volcanic areas due to land subsidence and sea level rise: A case study for Lipari Island (Italy). Terra Nova, 29, 44–51. doi: 10.1111/ter.12246
- ARPA FVG (Regional Agency for the Protection of the Environment of Friuli Venezia Giulia), 2018. *Studio conoscitivo dei cambiamenti climatici FVG – Primo report, marzo 2018*. Palmanova (UD), 348 pp.
- Bonaldo, D., Bucchignani, E., Pomaro, A., Ricchi, A., Sclavo, M., & Carniel, S., 2020. Wind waves in the Adriatic Sea under a severe climate change scenario and implications for the coasts. International Journal of Climatology, 40(12), 5389-5406. https://doi.org/10.1002/joc.6524
- Bezzi, A., Pillon, S., Popesso, C., Casagrande, G., Da Lio, C., Martinucci, D., Tosi, L., Fontolan, G., 2021. From rapid coastal collapse to slow sedimentary recovery: the morphological ups and downs of the modern Po Delta. Estuarine, Coastal and Shelf Science, 260, 107499. https://doi.org/10.1016/j.ecss.2021.107499
- Brambati, A. 2007. Studio di Verifica dello stato degli argini della bassa pianura friulana nel tratto compreso tra la foce del f. Tagliamento e Monfalcone con particolare riguardo all'arco lagunare. Dipartimento di Scienze Geologiche Ambientali e Marine dell'Università degli Studi di Trieste on behalf of Protezione Civile - Regione Autonoma Friuli Venezia Giulia.
- Carbognin, L., Teatini, P. and Tosi, L. 2004. Eustacy and land subsidence in the Venice Lagoon at the beginning of the new millennium, Journal of Marine Systems, 51(1–4), 345–353, doi:10.1016/j.jmarsys.2004.05.021.
- Church, J.A., Clark P.U., Cazenave A., Gregory J.M., Jevrejeva S., Levermann A., Merrifield M.A., Milne G.A., Nerem R.S., Nunn P.D., Payne A.J., Pfeffer W.T., Stammer D., Unnikrishnan A.S., 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin D., Plattner G.K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V., Midgley P.M. Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Cozzi, S., Giani, M., 2011. River water and nutrient discharges in the Northern Adriatic Sea: current importance and long term changes. Continental Shelf Research 31, 1881e1893.
- Da Lio C., Tosi L., 2018. Land subsidence in the Friuli Venezia Giulia coastal plain, Italy: 1992–2010 results from SAR-based interferometry, Science of The Total Environment, 633, 752-764, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2018.03.244.
- Fontolan G., Bezzi A., Pillon S., 2011. Rischio da mareggiata. In: Vitturi, A. (Ed.), Atlante Geologico della Provincia di Venezia. Cartografie e Note illustrative. Provincia di Venezia, pp. 581-600. ISBN 978-88-907207- 0-3
- Fontolan G., Bezzi A., Boccali C., Calligaris C., Colucci R.R., Cucchi F., Finocchiaro F., Martinucci D., Pillon S., Toffolon G., Turpaud P., Zavagno E., Zini L., 2015. Studio corredato da cartografia e relazione di sintesi geologica e geotematica sullo stato di fatto concernente la conoscenza d'insieme del territorio fisico regionale per la valutazione degli impatti dovuti ai cambiamenti climatici. Relazione di sintesi. Università degli Studi di Trieste, Dipartimento di Matematica e Geoscienze, 159 p. + cartografia allegata + opuscolo divulgativo.

- Fontolan G., Fattor F., Bezzi A., Bratus A., Casagrande G., Martinucci D., Pillon S., Tondello M., 2018. Studio di assetto morfologico e ambientale del Banco della Mula di Muggia. Regione Autonoma Friuli Venezia Giulia, Direzione Centrale ambiente ed energia.
- Gornitz V.M., Daniels R.C., White T.W., Birdwell K.R., 1994. The development of a coastal risk assessment database: vulnerability to sea-level rise in the U.S. Southeast. In: (Finkl C.W. Ed.) "Coastal hazards: perception, susceptibility and mitigation". Journal of Coastal Research, S. I. 12, 327-338.
- Lambeck, K., Antonioli, F., Anzidei, M., Ferranti, L., Leoni, G., Scicchitano, G., Silenzi, S., 2011. Sea level change along the Italian coast during the Holocene and projections for the future. Quaternary International, 232(1–2), 250–257. doi:10.1016/j.quaint.2010.04.026.
- Marocco R., 2009. Prima ricostruzione paleo-idrografica del territorio della bassa pianura friulano-isontina e della laguna di Grado nell'Olocene. Gortania, Geologia, Paleontologia, Paletnologia, 31: 69 - 86.
- Marocco R. and Pessina M., 1995 - Il rischio litorale nell'area circumlagunare del Friuli Venezia Giulia. Gortania, Atti Museo Friulano di Storia Naturale, 17: 5-35.
- Nicholls, R. J., Hanson, S. E., Lowe, J. A., Warrick, R. A., Lu, X. and Long, A. J.2014. Sea-level scenarios for evaluating coastal impacts, Wiley Interdisciplinary Reviews: Climate Change, 5(1), 129–150, doi:10.1002/wcc.253
- Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari, 2019. Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].
- Protezione Civile Regione Autonoma Friuli Venezia Giulia, 2010. Primi interventi di protezione civile in relazione al rischio di ingressione marina nelle aree costiere del Friuli Venezia Giulia e di esposizione al rischio della popolazione rispetto ad un evento meteo-marino estremo. http://www.protezionecivile.fvg.it/ProtCiv/GetDoc.aspx/48744/Rischio%20laguna_GB_2010_giornali.pdf
- Regione Autonoma Friuli Venezia Giulia, 1979. Studio dell'assetto fluviale e costiero della Regione Friuli – Venezia Giulia. Rapporto preliminare, seconda parte: parte costiera. ELC – Electroconsult, Studio Volta s.n.c.. Regione Autonoma Friuli – Venezia Giulia, Assessorato ai Lavori Pubblici, Servizio Idraulica, Trieste, 161 pp.;
- Regione Autonoma Friuli Venezia Giulia, 1985. Studio sedimentologico e marittimo costiero dei litorali del Friuli Venezia Giulia, ipotesi di intervento per il recupero ambientale e la valorizzazione della fascia costiera. A cura di Brambati A. Regione Autonoma Friuli Venezia Giulia, Direzione Regionale dei lavori Pubblici, Servizio dell'Idraulica, Trieste: 67 pp.
- Regione Autonoma Friuli Venezia Giulia, 2014. Progetto CAMIS – Attività coordinate per la gestione del fiume Isonzo. Studio morfologico del fiume Isonzo. Relazione Generale. Available online: http://www.camisproject.eu/modules/uploader/uploads/system_menu/files_sys/studio-morfologico-art-prima-fase_copy1.pdf.
- Regione Autonoma Friuli Venezia Giulia, 2016. *Piano stralcio per l'Assetto Idrogeologico regionale (PAIR) dei bacini idrografici dei tributari della laguna di Marano. Relazione tecnica, 154 pp.*
- Siche, I.; Arnaud–Fassetta, G. 2014. Anthropogenic activities since the end of the Little Ice Age: a critical factor driving fluvial changes on the Isonzo River (Italy, Slovenia). Méditerranée, 122, 183-199. https://doi.org/10.4000/mediterranee.7253
- Solidoro C., Del Negro P, Libralato S, Melaku Canu D (ed), 2010. *Sostenibilità della mitilicoltura triestina*. Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS, Trieste, 88 pp.
- Stammer, D., van de Wal, R. S. W., Nicholls, R. J., Church, J. A., Le Cozannet, G., Lowe, J. A., et al. (2019). Framework for high-end estimates of sea level rise for stakeholder applications. Earth's Future, 7, 923–938. https://doi.org/10.1029/2019EF001163
- Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nature Geoscience 2 (10), 681-686. https://doi.org/10.1038/ngeo629.

- Stravisi F. & Purga N., 1997 La stazione mareografica di Trieste – Porto Lido. Università degli Studi di Trieste Oceanografie e meteorologia Rapporto 60OM 97/7: 9 pp
- Thiéblemont, R., Le Cozannet, G., Toimil, A., Meyssignac, B. and Losada, I. J., 2019. Likely and high-end impacts of regional 1260 sea-level rise on the shoreline change of European sandy coasts under a high greenhouse gas emissions scenario. Water, 11(12), 2607, doi:10.3390/w11122607, 2019.
- Trobec, A., Busetti, M., Zgur, F., Baradello, L., Babich, A., Cova, A., Gordini, E., Romeo, R., Tomini, I., Poglajen, S., Diviacco, P., Vrabec, M., 2018. Thickness of marine Holocene sediment in the Gulf of Trieste (Northern Adriatic Sea). Earth System Science Data 2018, 10, 1077–1092. https://doi.org/10.5194/essd-10-1077-2018.
- Zanchettin D., Bruni S., Raicich F., Lionello P., Adloff F., Androsov A., Antonioli8 F., Artale V., Carminati E., Ferrarin C., Fofonova V., Nicholls R.J., Rubinetti S., Rubino A., Sannino G., Spada G., Thiéblemont R., Tsimplis M., Umgiesser Georg, Vignudelli S., Wöppelmann G., Zerbini S., 2021. Sea-level rise in Venice: historic and future trends. Natural Hazards Earth System Science, 21, 2643–2678, 2021 https://doi.org/10.5194/nhess-21-2643-2021

3.5 PO River delta site (Veneto part)

3.5.1 General site description

The Po Delta represents the final sub-basin subtending the entire Po River catchment, and it develops as a flat region with a surface that covers 1.6 % of the total Po basin, which is almost completely below the sea level (Piano di gestione del distretto idrografico del Fiume Po, Stato delle risorse idriche, 2016).

The Po River is the longest river in Italy and it receives most of its water supply from several watercourses, which originate from the Alps and Apennines and join the Po River after crossing the Padan plain. Therefore, its drainage area includes large territories in the western and central part of Northern Italy (Figure 3-65, left), and it extends until the Adriatic Sea where the delta develops.

*Figure 3-65: L**eft**, Po River catchment and main tributaries. **Right**, location and access routes. The grey line represents the boundary between the Emilia Romagna (south) and Veneto Region (north), where the active part of the Po Delta is located.*

3.5.1.1 Geographical and environmental setting

From a geographical point of view, the Po River Delta is located in Northern Italy, between the provinces of Venice and Ferrara. Its main access route is the Strada Statale Romea, n. 309, which connects Venezia to Ravenna, following the Adriatic coastline and crossing the Po branches (Figure 3-65, right). Other provincial routes start from SS 309 spreading towards east in the territory of the Delta.

The surface of the active Po Delta falls entirely in the province of Rovigo (Veneto Region), or Polesine, and it develops in the NS direction ranging between the Adige mouth and Po di Goro. In the past the territory between Po di Goro and the Reno River, which is part of the province of Ferrara (Emilia Romagna Region), represented the main Delta. Today this area is hydraulically disconnected from the Po River and regulated by hydraulic works.

The Delta is the result of natural and anthropogenic processes that have affected the mouth of the Po River for centuries (see Report 3.2.1 and 3.2.2 for the sedimentological and morphological evolution of the Delta), leading to its typical cuspid shape. In this region the Po River is divided into different branches: Po di Levante, Po di Maistra, Po di Pila (the easternmost mouth that subdivides in three more branches, Busa di Tramontana, Busa Dritta and Busa di Scirocco), Po di Tolle, Po di Gnocca, and Po di Goro. Between these deltaic branches there are both territories surrounded by fresh water and called islands ("isole"), and bodies of water that are connected in different measure to the sea, comprising valleys, lagoons and sacche. Among them are the two focus areas of the Change We Care project, Sacca del Canarin and Sacca di Goro.

Generally speaking, the Delta is a transitional environment between fresh and salt water. With exception of embankments and dunes, most of the delta plain is completely below the mean sea level, mostly because of subsidence processes, with maximum depths of -4 m in some points. The morphology is controlled by the interaction between sediments and water, as well as among depositional processes, stabilizing action of the vegetation and destructive power of the flood surges. As a result, the Po delta shows all morphological features of transitional environment like tidal flats, saltmarshes and and sand banks / barrier islands (scanni), and it hosts high level of biodiversity. Most of the coastline is characterized by sandy beaches and mouth bars (scanni), except for some rigid hydraulic works along the coastline that are built to regulate some of the lagoon and fluvial mouths.

From an environmental point of view, the Po Delta, with its interconnection of aquatic and land habitats, of fresh and salt water, represents a particularly important environmental and ecological system. It is an extensive wetland area for rest, wintering and reproduction along the migratory routes. Thanks to the variety of its environments, several protected areas have been established in the last decades:

In 1999 the Po Delta was included among the Italian World Heritage Sites by UNESCO. Furthermore, since 2015, it has been part of the natural reserves designated by the MaB UNESCO (Man and Biosphere), which is a world network of Biosphere Reserves including internationally recognized terrestrial, marine and coastal ecosystems. The MaB reserve of the Po Delta is a large area covering territories of the Veneto and Emilia Romagna Regions, with a total surface of 138,000 ha, of which 30% are located in Emilia Romagna and 70 % in Veneto. From an administrative point of view, the territory is divided between the Veneto and Emilia Romagna Regions, which manage independently the parts under their jurisdiction.

The area is one of the most important ecosystem in Europe, with 31 Sites of Community Importance (SCI), 22 Special Protection Areas (SPA) and 13 Natural Reserves, where over 450 species of resident and migratory birds live or breed. It also hosts over than 40 species of mammals, while the flora of the area includes almost 979 species of plants (Natereg project).

The Po Delta of the Veneto Region represents a unique large Site of Community Importance and Special Protection Area. It includes 22 protected habitats, (of which six are priority habitats), and 102 protected species (of which four are priority). The Special Protection Area overlap partially the SCI, distinguishing from this one for its minor extension along the main branch of the Po River (until Papozze), for the inclusion of all the secondary branches of the Po (enclosing Po di Levante) and for the dune system in Ariano nel Polesine. Besides the delta system, this territory comprises the coastal dune systems, the valleys, the sandy spits and the fluvial islands as well as the floodplains and oxbows. Halophisous and psammophilous plants colonize the singular sand formations at the fluvial mouths and along the margins of the lagoons. In addition, remnants of ancient forests are present in some parts too. The valley part is characterized by the presence of a large complex of reeds, sandbanks, canals and marshes. The natural landscape includes water bodies with submerged Macrophyte vegetation and wide flat islands that host halophilous types and syntypes. The priority habitat “coastal lagoon” is the most representative one due to its coverage (45%), and it is largely present in the focus area of this report Sacca del Canarin (Figure 3-66).

Figure 3-66: Po Delta Park of the Veneto Region (green) and Po Delta Park of Emilia Romagna (red). SCI-SAC and SPA are highlighted with a dashed pattern. Location of the two focus sites of Canarin and Goro (Regional webgis)

3.5.1.2 Administration, main economic activities, recent development, land use

The Po Delta of Veneto Region extends for about 470 square kilometers, including several valleys and lagoons. There are over 73 thousand inhabitants in the entire delta area. The territory is primarily agricultural and the population density is quite low with urban centers consisting in small towns, hamlets, and isolated houses (Figure 3-67).

Figure 3-67: Satellite image of the Po Delta. The Fish Valleys are highlighted together with the lagoons and Sacche. Most of the territory is completely cultivated, while the urbanization is low. (Quaderni Cà Vendramin)

In the first half of the 20th century, extensive land reclamation works involved the lowlands with the drainage of marsh areas and fish valleys. Today most of the arable lands in Polesine is occupied by monocoltures, consisting in relatively large farms, with a low incidence of tree crops. Maize, wheat and soya prevail throughout the territory, and they are mainly cultivated in large areas alternated with forage crops. Vegetables are widespread close to the coastal areas, thanks to the sandy soil, and they consist in high-quality products, such as asparagus, garlic, pumpkins, watermelons, and melons. Important is the presence of rice fields, fundamental also for the conservation of some bird's species, although they are under the growing pressure of the salt intrusion. In the past, beet plantations were common, and they were connected to the sugar refineries, which only recently have been dismantled. In the Po River Delta, as in whole the Po plain, the number of small-medium livestock farms has reduced in the last decades, leaving the space to larger farms. Poultry and cattle farms are present, but the latter ones are not connected to the milk production.

Additional activities typically related to fishing, aquaculture, and tourism have occupied a prominent role in the development of the area. A significant production sector includes the fish supply chain, consisting of professional fishing activities and companies operating in the processing and marketing of fish products. The fish sector production, which encompasses traditional and typical products, is quite large and well diversified. In particular aquaculture is well developed in the fishery ponds with precious and common fish species, whereas mussel-farming is widespread in the lagoons (i.e. mullet from Polesine, clams from Polesine, blue fish, mussels from Scardovari, marinated eels from Delta del Po, sardines and marinated anchovies from the Po Delta). The production is based on fishing cooperatives. The most important fish market is located in Porte Tolle.

Tourism in the area is another important economic source, and it is connected mainly to the valorization of the Park from a historical and naturalistic point of view.A secondary sector based on small and very-small enterprises has developed in various fields such as the chemical, metalworking and textile one, and it is mainly founded by local entrepreneurs.

3.5.1.3 Main problems and management objectives

The morphological and environmental features of the lagoons represent a peculiar aspect in the management objectives of the transitional areas of the Po Delta region. In this respect, some crucial features can be highlighted:

- Low depth (1-2 m)
- Connection to the sea through one or more mouths, which regulate the exchange of marine water.
- Important annual temperature variation.
- Large salinity variation.

The main problems of the lagoons are connected to the intrinsic and highly variability of their environmental and morphological conditions that tend to change quickly in response to the external factors. In particular:

- the salinity levels are extremely mutable and depend on the water exchanges with the sea and Po river (through floods);

- the oxygen content in the shallowest areas has a large impact on the production activities;
- the water quality is threatened by algae blooming and nutrients (phosphates and nitrates) coming from the fluvial waters;
- the infilling of the lagoons, due to sediment deposition, influence the internal circulation and consequently the fishing and shell-farming production;
- the continuous erosion of the external spits that usually protect the lagoons from the open sea threaten the same existence of the lagoon areas.

One of the main challenges is the stabilization of the lagoon environment for the economic and development purposes, without deteriorating their value, especially considering the mutable conditions that the Climate Change will bring.

The phenomenon of the salt intrusion mainly affects the internal area of the Po River Delta, and in recent decades. The main impacts are on agriculture influencing the withdrawals for irrigation in the Po Delta. On the other hand, the intrusion of the saline water along the river mouths of the Po River, by modifying the environmental and trophic conditions of the delta branches, often leads to favourable situations for the settlement of juveniles of marine / brackish species, some of which of considerable interest for the local economy. In fact, thanks to its mixture of fresh and salty water, the Po branches are able to host large settlements of clam juveniles (the so called nurseries) Tapes philippinarum, becoming an area of economic interest, as it represents an exploitable natural fishing area.

3.5.2 Assessment of sea level rise scenarios in the considered coastal and transitional areas

To assess the sea level rise scenarios and their effects on the Po Delta coast, the Veneto Region agreed with the leader partners of the project and of the WP4.2 to use existing analyses, as this task was not initially contemplated among the duties of the group. Therefore, a detailed inundation map proposed in 2017 by Marsico et al. was considered in this report, showing the drowning lands for three future sea level rise scenarios.

Relative sea level can change over a wide range of timescales from seconds to centuries, and a significant sea level variability can occur over years or even several decades due to a range of processes and large-scale atmospheric circulation. When considering future sea level variations, a multidecadal evaluation over 30 or 100 years is a reliable option and a common practice is to consider the effects of the sea level rise in 2100 (or in decades 2080-2100), although sometimes intermediate predictions can be offered in 2050.

Recent papers (Table 1) have investigated the impacts of the sea level rise along the Adriatic coastline, and some of them have included the Po River Delta in their analysis, computing the extension of the potential flooding, rating the hazards that will affect the region in the future, and deriving a prediction of the forthcoming risks. Therefore, an analysis of these works can give a fair overview of the sea level rise scenarios in the considered coastal and transitional region.

There are several different methods of determining appropriate sea level scenarios and these include using observed data, process-based or statistical models, numerical models or synthetic methods encompassing extreme events. Relative sea level is then the sum of two major components: Global-mean sea level change and Regional and/or local spatial variations.

Sea level rise scenarios are often built based on the predictions made by the IPCC either assuming that the absolute values of the local sea level rise would be similar to the mean global variations or using a cascade of numerical models to compute the regional sea level increase. When considering the worst case of the emission path theorized by the IPCC (RCP 8.5), the absolute sea height alongside the Delta coastline ranges from 0.53 (minimum value) to 0.97 m (maximum value). A most severe scenario comes from the prediction of Rahmstof (2007) leading to a sea level of 1.4 m in 2100.

Less conservative predictions derive by different IPCC scenarios, as done by some of the works dealing with the Po Delta (Torresan et al. 2019, Gallina et al. 2019, 2020), where the A1B-SRE emission scenario of the IPCC served as the forcing input of global circulation models used to simulate the atmospheric and ocean circulation at a global scale. In such cases, downscaling techniques have been applied to convert coarser resolution data of Global Climate Models (GMC) to a higher resolution by nesting high-resolution limited area models in GCMs. Regional Climate Models have been successively used to simulate the effect of climate changes in limited and high-resolution areas. The sea level predicted by these works along the Adriatic coast is between 0.17 and 0.42 m. These works based on numerical simulations are also able to evaluate the variations of the storm surges and erosion intensity by providing the significant height of the waves and the shear stress at the bottom as also done in WP 4.1 of the Change We Care project.

Sea level rise in 2100 can be derived by inferring the observed data collected in one or more stations along the Adriatic Sea. The increase rates vary from 1.3 mm/year for long term predictions up to 3.8 mm/year for short term predictions.

Climate scenarios -future projections	Sea level rise Dh (with respect to the current level)	Year	Used in
ARS5- RCP 8.5 [min – max]	[0.53 -0.97] m	2100	Marsico et al. (2017), Antonioli et al. (2017) Da Lio et al. (2019) considering 5mm/year as mean rate of increase to 2100
Multi-cascade models starting from IPCC, A1B-SRES (current RCP 6)	[0.17-0.42] m	2100	Torresan et al. 2019, Gallina et al. 2019, 2020
Rahmstorf (2007)	1.4 m	2100	Marsico et al. (2017), Antonioli et al. (2017)
Short term trend	3.8 mm/year□ ~0.31 m	2100	Rizzi et al. (2017) Da Lio et al (2019) for the ongoing long-term scenarios
Long term trend	1.3 mm/year□ ~0.11 m	2100	Rizzi et al. (2017) Da Lio et al (2019) for the ongoing short-term scenarios

In this report we reproduce a detailed inundation map proposed in 2017 by Marsico et al., showing the present coastline of the Po Delta and its estimated future position due to the extension of land flooding for three different sea level rise scenarios.

3.5.3 Long-term sediment fluxes and identification of erosional and depositional hot spots

An assessment of the morphological response of the Po River Delta to the future sea level rise was not possible within the activities of this project, considering the morphological complexity of the region, combined with the fragmentation of information on sediment fluxes, and the lack of a morphological model for the whole delta. However, some general observations can be drawn on the basis of past studies and recent observed trends commented in Report 3.2.1 and 3.2.2.

The relative sea level increase would presumably bring to a decline of salt marshes and tidal flats, and to a morphological simplification of the lagoons, deriving from the flattening of their bottom and the siltation of the channels. An anticipation of this trend has been observed before the 70's, when the Po Delta experienced high subsidence rates, sinking for several decimeters, and going under the water. During that period, a strong degradation of the coastal dunes and barriers was observed, together with the loss of tidal landforms.

The trend that was reduced thanks to a change of policy and several concrete interventions can become worst in the future, especially in case of erosion, submergence or overstepping of the barrier islands due to the sea level rise, which now provide a protective function to the lagoons. Finally, since the morphological response of the transitional system is strongly entangled with the sediment fluxes coming from the rivers, the natural resilience of the lagoons would depend deeply on the sediment availability.

The evaluation of the sediment transport in the Po Delta region is the object of the institutional activities currently carried out by the Authority for the Po River basin (Adpo), which is developing a plan for the sediment management dealing also with the expected future changes.

3.5.4 Short term and long term vulnerability

3.5.4.1 Short-term vulnerability

The Coastal Vulnerability Index (CVI) is one of the simplest and commonly used methods to assess coastal vulnerability to sea level rise driven erosion and/or inundation. In the framework of the Change We Care project, the working group of Veneto Region, supported by the University of Trieste, has computed this index for the Po Delta following the methodology developed by the Friuli Venezia Giulia Region and the University of Trieste and based on the Gornitz approach. The potential vulnerability is defined as a linear combination of morphological and evolution variables, which measure the **natural susceptibility of the**

coastal regions to the erosion and overstepping. The presence of natural and rigid protections leads to a reduction of the potential vulnerability, resulting in what it is called real vulnerability.

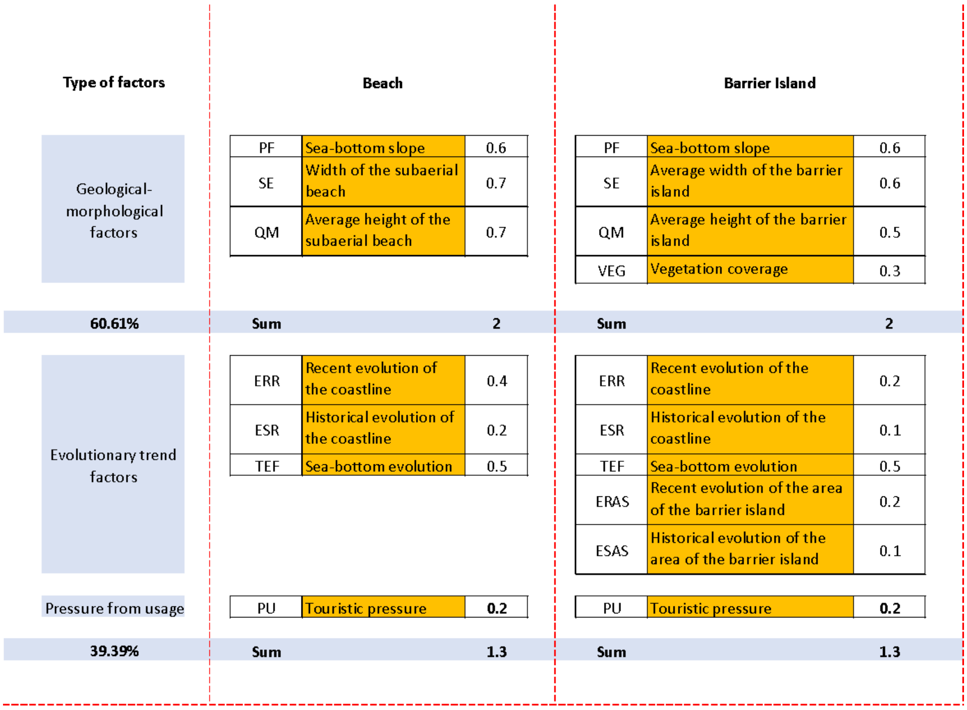
The methodology is fully described in chapter 5.4 and here the main outcomes for the Po River Delta are presented and commented.

The different variables that concur to the vulnerability assessment come by the analysis of several data consisting of:

- Orthophoto and, when available, DTM between the 1978 and 2018 (1978, 1996, 2012 and 2018).
- Bathymetric profiles analyzed and already presented in Fontolan et al. (2014).
- Touristic and land use information.
- Cadaster of the protection works along the coast.
- Cadaster of the dunes (updated to the year 2014 and here only verified)

3.5.4.2 Potential vulnerability assessment

To assess the potential vulnerability, the coast of the Po Delta has been subdivided in different cells having homogeneous morphological setting and similar trends. The division has followed the one presented in the “Geodatabase gestionale per la zona costiera del delta del Po” by Fontolan et al. (2014), but updating the classification to the most recent surveys (lidar from 2018) and integrating the data with new elaborations. In particular, a further distinction of the cells has been carried out, distinguishing between two categories comprising “linear shoreline” and “barrier islands”. The choice has been driven by the particular configurations of the delta, characterized both by sand beaches and transitional environments often fronted by barrier islands. The variables considered in the assessment of the potential vulnerability are slightly different in the two cases and they are listed in Figure 3-68 together with the corresponding weights, which has been chosen in agreement with Friuli Venezia Giulia Region.



Type of factors	**Beach**			**Barrier Island**		
Geological-morphological factors	PF	Sea-bottom slope	0.6	PF	Sea-bottom slope	0.6
	SE	Width of the subaerial beach	0.7	SE	Average width of the barrier island	0.6
	QM	Average height of the subaerial beach	0.7	QM	Average height of the barrier island	0.5
				VEG	Vegetation coverage	0.3
60.61%	**Sum**		**2**	**Sum**		**2**
Evolutionary trend factors	ERR	Recent evolution of the coastline	0.4	ERR	Recent evolution of the coastline	0.2
	ESR	Historical evolution of the coastline	0.2	ESR	Historical evolution of the coastline	0.1
	TEF	Sea-bottom evolution	0.5	TEF	Sea-bottom evolution	0.5
				ERAS	Recent evolution of the area of the barrier island	0.2
				ESAS	Historical evolution of the area of the barrier island	0.1
Pressure from usage	PU	Touristic pressure	**0.2**	PU	Touristic pressure	**0.2**
39.39%	**Sum**		**1.3**	**Sum**		**1.3**

Figure 3-68: Methodology to assess the coastal potential vulnerability of the shoreline and barrier islands in the Po Delta region

Photointerpretation and DTMs were employed to delineate the barrier islands and the shoreline throughout the selected years, allowing for the evaluation of the morphometric parameters of the identified units (mean width of the subaerial shoreline, mean width of the barrier islands, average height, and vegetation coverage) and for the estimation of their multi-decadal evolution. In particular, QGIS analyses were carried out to determine the coastline variation (historical and recent erosion/accretion), surface changes of the identified barrier islands, and to combine and aggregate the different information with previous evaluations (e.g. sea-bottom slope). Overall, 21 cells have been identified along the Delta coastline, encompassing 16 barrier/ or similar to barrier islands and 5 linear shoreline parts (see Figure 3-69 and Table 8). Some of them have been subject to large changes since 1978, evolving from multiple units to a single one or vice versa. Tracking such temporal variations of the morphological units has been crucial to quantify the evolutionary trend of the coast.

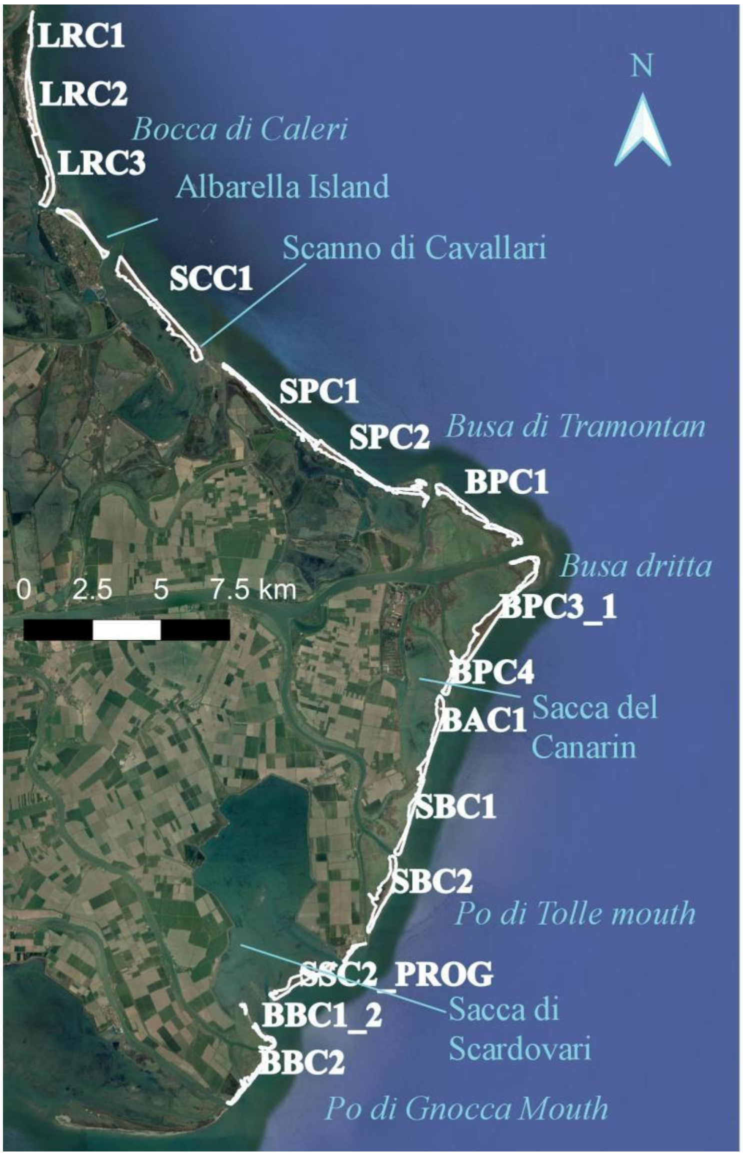


Figure 3-69: Identified cells along the Po River Delta

Table 8: Identified cells along the Po Delta coastline

Cell 2018	Municipality	Definition	Type
LRC1	Rosolina	Litorale di Rosolina Mare	beach
LRC2	Rosolina	Litorale di Rosolina Mare	beach
LRC3	Rosolina	Litorale di Rosolina Mare	beach
IAC1	Rosolina	Isola di Albarella	beach
SCC1	Porto Viro	Scanno Cavallari	barrier island

SPC1	Porto Tolle	Litorale di Barbamarco	barrier island
SPC2	Porto Tolle	Litorale di Barbamarco	barrier island
SPC3_0	Porto Tolle	Litorale di Barbamarco	barrier island
BPC1	Porto Tolle	Bocche del Po della Pila	barrier island
BPC2_0	Porto Tolle	Bocche del Po della Pila	barrier island
BPC3_1	Porto Tolle	Bocche del Po della Pila	barrier island
BPC3	Porto Tolle	Bocche del Po della Pila	barrier island
BPC4	Porto Tolle	Bocche del Po della Pila	barrier island
BAC1	Porto Tolle	Canarin	barrier island
SBC1	Porto Tolle	Bonelli	barrier island
SBC2	Porto Tolle	Bonelli	barrier island
SSC1	Porto Tolle	Sacca di Scardovari	beach
SSC2_PROG	Porto Tolle	Sacca di Scardovari	barrier island
BBC1_2	Porto Tolle	Bonello Bacucco	barrier island
BBC2	Porto Tolle	Bonello Bacucco	barrier island
BBC3_1	Ariano nel Polesine	Bonello Bacucco	barrier island

Figure 3-70 and Figure 3-71 report an example of the procedure used to derive the morphometric and evolutionary information from the analyzed dataset and they refer to the barrier islands enclosing Sacca del Canarin. The pictures describe the delineation of the cells in 4 temporal steps, the derived position of the coastline to assess the retreat and progradation of the coast, the bathymetric sections in front of the cells used to compute the sea-bed information, the centerlines from which the mean width has been calculated, and the DTM employed to derive the mean height.

As already discussed in WP3.2, the morphological configuration of Sacca del Canarin has undergone profound changes in the period 1978-1996 and relatively lower variations later on, when the general setting has been influenced by several human interventions. For example, the presence of specific barriers has induced local sediment accumulations in proximity of the Enel channel (Cell BPC4), while the northern part of “Scanno del Canarin” (BAC1) has been subject to a series of recent nourishments that have contributed to increase the surface of the barrier island.

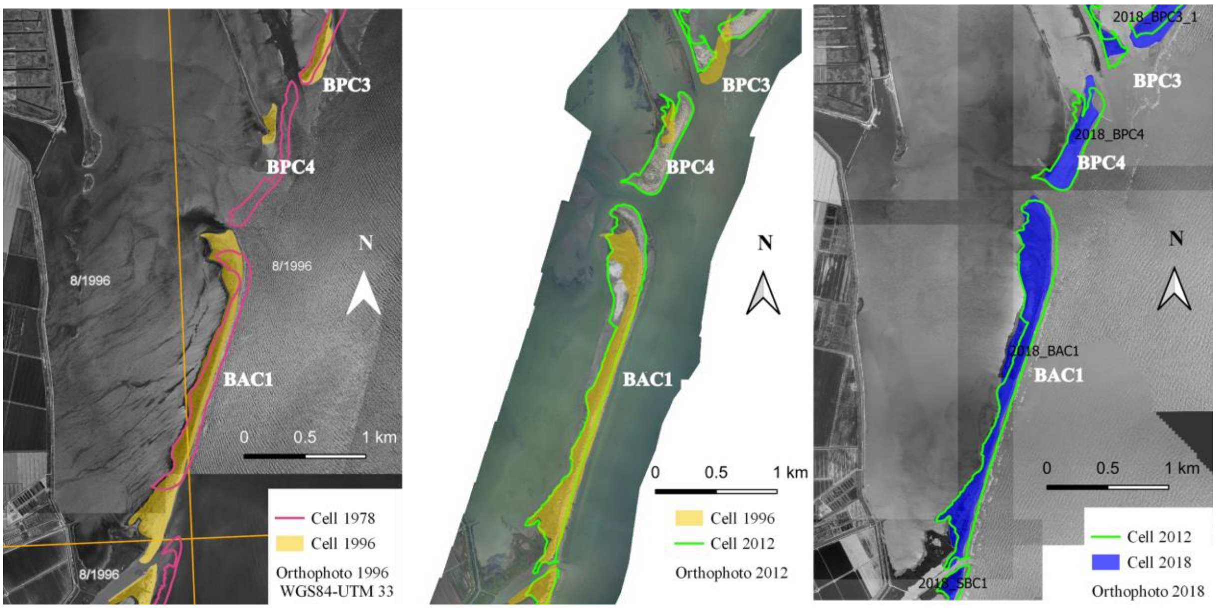


Figure 3-70: Temporal evolution of the barrier island of Sacca del Canarin 1978-2018

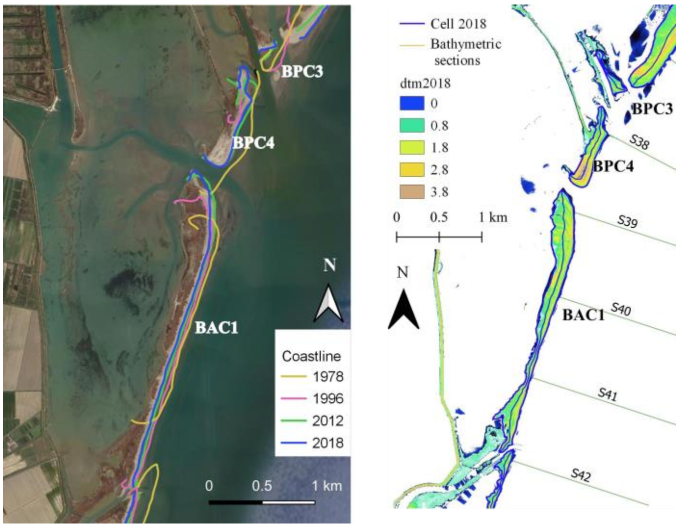


Figure 3-71: Left, coastline from 1978 to 2018. Right, DTM (2018) and bathymetric sections used for Sacca del Canarin,

Figure 3.72 and Figure 3.73 give a brief overview of the historical and recent trends observed in the Po River Delta both in terms of shoreline variations and surface change of the barrier islands. As already pointed out in WP3.2, the data speak of a very dynamic system characterized by some regions stabler than others, while other regions shrinking because sediment deprived. It is worth noting the nose of the Po River Delta, corresponding to Po di Pila, shows an extremely variable behavior, since it has been always evolved naturally, without any stabilizing interventions or human modifications.

The extensive interventions realized in the northern part of the Delta to protect the touristic shoreline result in a more rigid configuration of some areas (e.g. Rosolina) and in the accretion of the neighboring islands, which have benefited from the protections put in place in the adjacent units. Similarly, continuous interventions have been carried out in the lagoon of Scardovari, whose island (SCC2_PROGR) is maintained in its specific location with periodic nourishments and reprofiling. Conversely, the Po Delta nose is subject to a high variability connected to the high sediment flux flowing through the main Po outlet Po di Pila. The southern part of the Delta has shown and continue to exhibit some criticalities due to high erosion rates.

Before calculating the potential vulnerability as linear combination of the computed parameters, each variable was converted to a scale of values ranging from 0 to 4, corresponding respectively to the lowest and highest vulnerability class. The normalization has been carried out by using a linear interpolation of the measured values, assuming that the coastal susceptibility to erosion increases for low values of some morphological parameters, such as width and height of the barrier islands, while it decreases for higher value of such variables. The “worst” and “best” morphological conditions were based on the measurements obtained in the whole north Adriatic Sea to obtain results comparable to other locations (e.g. Friuli Venezia Giulia Region).

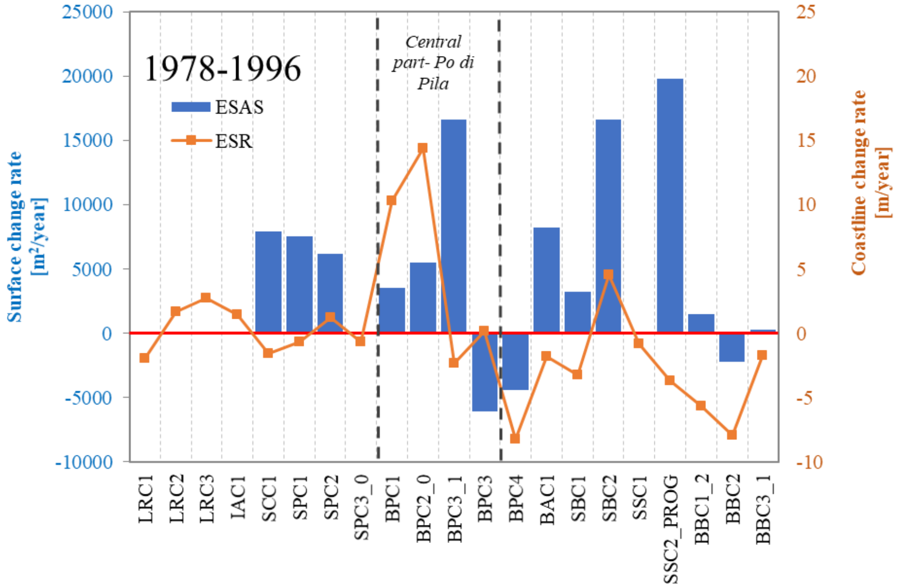


Figure 3-72: historical evolution of the coastline (line) and the aerial extension of the barrier islands (bars). Rate of the variations. The cells are ordered from North (LRC1) to South (BBC3_1)

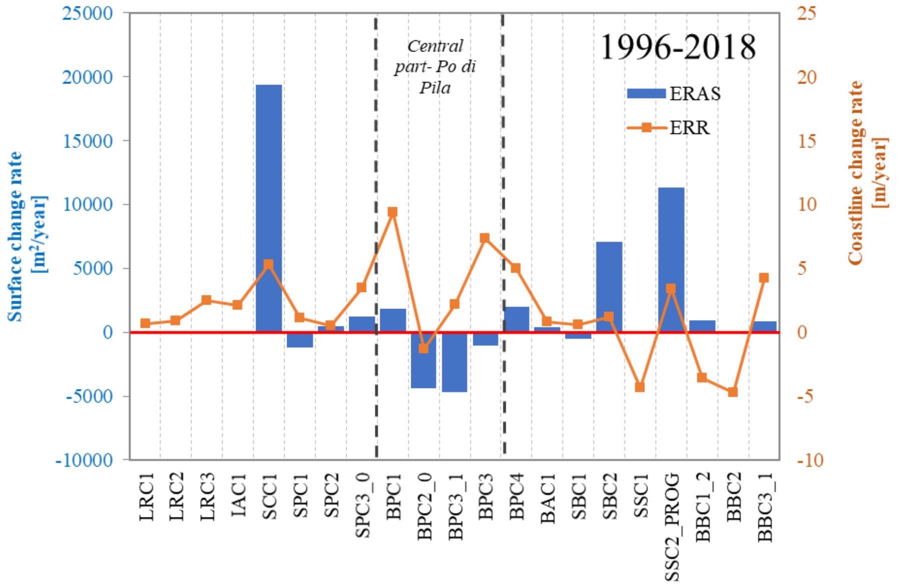


Figure 3-73: recent evolution of the coastline (line) and the aerial extension of the barrier islands (bars). Rate of the variations. The cells are ordered from North (LRC1) to South (BBC3_1)

Parameters			**Low vuln.**	**High vuln.**	**Regression**	
			0	**4**	**m**	**q**
Average height	(m)	**QM**	2.5	0.0	-1.6	4.0
Width (beach - barrier island)	(m)	**SE**	140.0	0.0	0.0	4.0
Historical evolution of the area of the barrier islands	(m^2/year)	**ESAS**	17426.4	-10038.5	0.0	2.5
Recent evolution of the area of the barrier islands	(m^2/year)	**ERAS**	17426.4	-10038.5	0.0	2.5
Historical evolution of the coast	(m/year)	**ESR**	5.0	-5.0	-0.4	2.0
Recent evolution of the coast	(m/year)	**ERR**	5.0	-5.0	-0.4	2.0
Sea-bottom evolution	(m^3/m/year)	**TEF**	30.0	-30.0	-0.1	2.0
Sea-bottom slope	(-)	**PF**	0.0	0.0	2.1	11.8
Touristic pressure	(presence/m)	**PU**	0.0	400.0	0.0	0.0

Table 9: Parameters used to compute the potential vulnerability (name, unit of measure and abbreviation); "best" values for the lowest class of vulnerability (column 0), "worst" values for the highest class of vulnerability (4), and parameters for the linear function (y=mx+q).

Table 9 summarizes the considered variables, the range of values used for the normalization, and the parameters (m and q) derived for the linear functions (for the sea-bottom slope a logarithmic function was defined). The vegetation coverage was classified as absent (4), scarce (3), discontinuous (2), abundant (1) and total (0).

Table 10 contains the normalized values of the parameters used to compute the potential vulnerability and its final value (VP). The values used to weight each variable are the ones presented in Figure 45.

Split18	**QM**	**SE**	**ESAS**	**ERAS**	**ESR**	**ERR**	**TEF**	**PF**	**PU**	**VEG**	**VP**
LRC1	*0.0*	*3.4*			*2.8*	*1.7*	*1.8*	*2.7*	*1.0*	*4.0*	*6.33*
LRC2	*0.3*	*1.1*			*1.3*	*1.6*	*3.7*	*2.7*	*1.5*	*4.0*	*5.64*
LRC3	*0.0*	*0.0*			*0.9*	*1.0*	*1.0*	*1.8*	*0.2*	*3.0*	*2.19*
IAC1	*0.8*	*1.0*			*1.4*	*1.2*	*2.4*	*1.5*	*1.4*	*4.0*	*4.41*
SCC1	1.4	0.0	1.4	0.0	2.6	0.0	1.8	1.8	0.0	3.0	3.93
SPC1	1.4	1.0	1.4	2.7	2.3	1.5	1.5	1.9	0.0	2.0	5.02
SPC2	1.3	1.0	1.6	2.5	1.5	1.8	1.2	2.1	0.0	3.0	5.16
SPC3_0	1.4	1.4	2.5	2.4	2.3	0.6	0.0	1.8	0.0	2.0	4.32
BPC1	1.8	0.5	2.0	2.3	0.0	0.0	1.9	2.3	0.0	2.0	4.78
BPC2_0	1.9	1.1	1.7	3.2	0.0	2.5	1.6	2.5	0.0	3.0	6.13
BPC3_1	1.6	0.0	0.1	3.2	2.9	1.1	0.0	2.6	0.0	2.0	4.16
BPC3	2.4	2.6	3.4	2.7	1.9	0.0	0.0	2.6	0.0	2.0	5.99
BPC4	0.9	0.5	3.2	2.2	4.0	0.0	0.2	2.0	0.0	3.0	4.15
BAC1	1.8	0.4	1.3	2.5	2.7	1.7	1.4	2.2	0.0	1.0	4.71
SBC1	1.9	1.4	2.1	2.6	3.3	1.8	2.9	2.4	0.0	2.0	6.69
SBC2	1.2	0.0	0.1	1.5	0.2	1.5	0.0	2.6	0.4	2.0	3.50
SSC1	*1.8*	*2.7*			*2.3*	*3.7*	*2.5*	*2.4*	*0.4*	*4.0*	*7.85*
SSC2_PROG	2.4	0.0	0.0	0.9	3.5	0.6	0.3	1.4	0.0	2.0	3.50
BBC1_2	2.5	2.7	2.3	2.4	4.0	3.4	0.0	1.2	0.0	4.0	6.60
BBC2	2.3	2.1	2.9	2.5	4.0	3.9	4.0	2.2	0.0	3.0	8.62
BBC3_1	2.2	2.6	2.5	2.4	2.7	0.3	0.0	1.5	0.0	1.0	4.94

Table 10: Normalized parameters for each cells and potential vulnerability index

Four categories of vulnerability were considered, based on the classification proposed for the northern part of the Veneto coastline (master thesis Busetti, 2017):

- Low vulnerability: V≤3.3
- Moderate vulnerability: 3.3<V≤6.6
- High vulnerability 6.6<V≤9.9
- Very high vulnerability: V>9.9

As visible from the map, most of the Po Delta Coast falls in the moderate class of vulnerability (between 3.3 and 6.6), some in the high class (between 6.6 and 9.9) and only few in the low class (<3.3).

The methodology leads to a classification that reflects in large parts the critical areas highlighted also by the guidelines for the “Integrated coastal zone management of the Veneto Region” (Ruol et al. 2016), but it updates this assessment to the latest available surveys, providing at the same time a quantifiable index based on a larger set of geomorphological parameters.

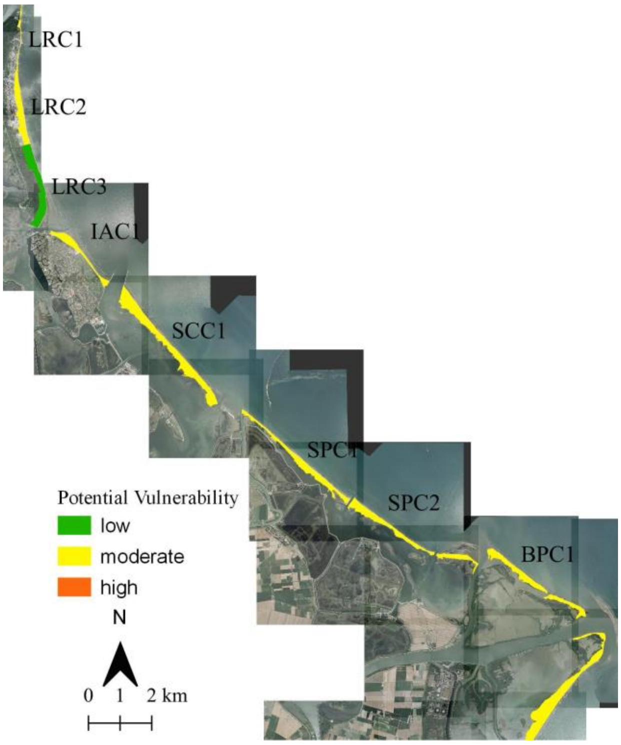


Figure 3-74: Potential vulnerability: northern part of the Po Delta

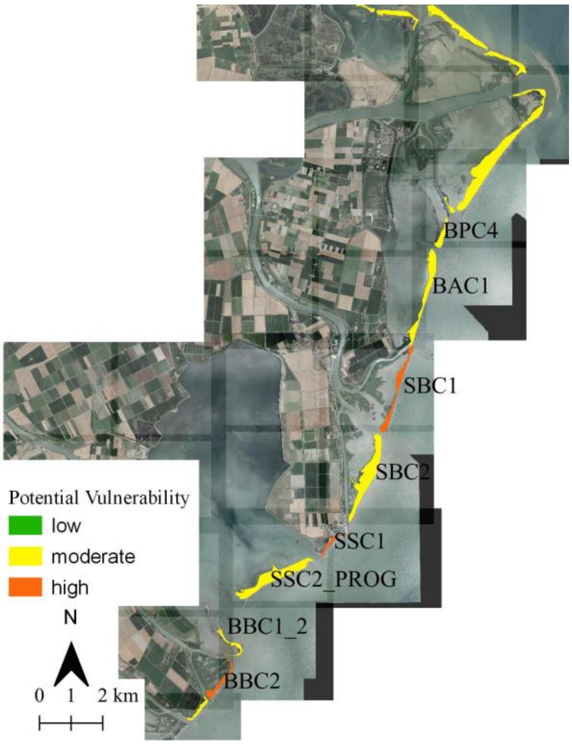


Figure 3-75: Potential vulnerability: southern part of the Po Delta

3.5.4.3 Real vulnerability

Dunes and defense structures tend to reduce the potential vulnerability by offering reinforcement to the coast and protecting the land against potential ravages by storm waves from the sea. The real vulnerability is thus computed by subtracting the contribution of each element defending the coast from the potential vulnerability. Several parameters are contemplated to define the efficacy of these elements and to quantify their contribution to reducing vulnerability.

The factors used here to characterize the **dunes** are steepness (RIP), presence of small dunes (AvInc), vegetation coverage (Veg), and discontinuity (Open), in addition to the average height of the dunes (QN). Together these data define the grade of stability of the dunes and their ability to cope with severe events. For this work, the data were retrieved by the cadaster of dunes developed by Fontolan et al. 2014, and they were verified only through aerial photos and DTMs since field works were not possible due to the pandemic restrictions.

Each variable was classified in a scale of values going from 0 to 4, where the highest class corresponded to dunes that were less stable (lower percentage coverage, higher presence of discontinuities, absence of small dunes and high steepness are parameters characterizing weak dunes). The efficacy of each dune was then defined as the sum of the 4 normalized parameters, divided by the maximum value of protection that they could provide (sum of the parameters/20). The contribution of each dune was then evaluated as the product of the efficacy, normalized height, and a constant that made the final value comparable to the potential vulnerability.

For sake of brevity here the normalized parameters pertaining to the dunes are presented considering only their aggregated value for each cell, computed as the average values of the total dunes falling in each morphological unit.

Split18	RIP	QN	AvInc	Veg	Open	IES	EffDun	Contr
LRC2	0.00	3.86	0.00	1.00	3.43	0.28	12.73	2.10
LRC3	3.14	2.29	1.71	0.14	3.43	0.53	7.54	2.40
IAC1	2.00	2.00	0.00	1.00	4.00	0.44	6.60	1.73
SCC1	1.74	1.37	0.58	1.79	3.68	0.49	4.52	1.26
SPC1	0.65	1.29	0.18	2.24	3.88	0.43	4.27	1.16
SPC2	0.57	1.43	0.00	0.43	4.00	0.31	4.71	0.90
SPC3_0	1.00	1.00	1.00	3.00	4.00	0.56	3.30	1.11
BPC1	3.00	1.00	1.00	3.00	4.00	0.69	3.30	1.36
BPC2_0	0.00	1.00	0.00	2.00	4.00	0.38	3.30	0.74
BPC3_1	2.50	1.50	0.50	1.00	4.00	0.50	4.95	1.55
BAC1	0.43	1.14	0.14	2.57	3.14	0.39	3.77	0.87
SBC1	0.00	1.50	0.00	1.50	3.00	0.28	4.95	0.87
SBC2	2.50	1.50	1.88	1.50	3.25	0.57	4.95	1.56

Table 11: List of the aggregated dunes present in the considered cells

Similarly, the contribution of **rigid protection** depends on their characteristics, such as location (sea protection, longshore protection, inland protection) and height. Here we present the table of the barriers considered in the Po River Delta.

id	Type	Class	Split18	QN	CiQn	Cont
3	soffolta	A mare	SPC1_D	2.00	1.00	3.33
4	soffolta	A mare	SPC2_D	2.00	1.00	3.33
5	soffolta	A mare	SPC3_0_D	2.00	1.00	3.33
6	scogliera	Radente	LRC1	0.26	0.21	0.69
7	scogliera	Radente	LRC1	0.47	0.38	1.25
8	scogliera	Retrospiaggia	LRC1	4.00	3.20	10.64
9	scogliera	Retrospiaggia	LRC1	4.00	3.20	10.64
10	scogliera	Retrospiaggia	LRC1	4.00	3.20	10.64
12	scogliera	Radente	IAC1_D	2.84	2.27	7.55
13	scogliera	Radente	BPC4	2.41	1.93	6.41
15	scogliera	Radente	SSC2_PROG	1.42	1.14	3.78
16	scogliera	Radente	SSC2_PROG	0.71	0.57	1.89
17	*scogliera*	*Radente*	*SSC2_PROG*	*1.61*	*1.29*	*4.28*
18	saccata	Radente	SSC1_D	0.75	0.60	2.00
19	soffolta	A mare	LRC1	2.00	1.00	3.33
20	soffolta	A mare	LRC1	2.00	1.00	3.33
21	soffolta	A mare	LRC1	2.00	1.00	3.33
22	soffolta	A mare	LRC1	2.00	1.00	3.33
23	scogliera	Radente	SSC2_PROG	0.71	0.57	1.89
24	scogliera	Radente	LRC2_D	4.00	3.20	10.64
25	argine	Retrospiaggia	LRC1	4.00	3.20	10.64
26	argine	Retrospiaggia	LRC1	4.00	3.20	10.64
27	argine	Retrospiaggia	LRC1	4.00	3.20	10.64
28	argine	Retrospiaggia	LRC2_D	4.00	3.20	10.64
29	argine	Retrospiaggia	LRC1	4.00	3.20	10.64
30	argine	Retrospiaggia	IAC1_D	4.00	3.20	10.64
31	argine	Retrospiaggia	LRC2_D	4.00	3.20	10.64

Table 12: List of the defense works considered in the Po River Delta

An example of a barrier island protected by defense works and dunes is provided in *Figure 52* and *Figure 53*, which show how the vulnerability is influenced by the stabilizing effect of the dunes and by the measures put in place along the coastline. Spiaggia di Barricata (SBC2) has a large system of dunes subject to constant mantainance works by the Region. As shown in the map, they contribute to the the overall reduction of the cell vulnerability.

A more detailed analysis would require a further division of the cells in sub-units, to highlight the portions of islands or shorelines that are more exposed to erosion with respect to the others. Furthermore, a specific assessment of each construction is fundamental to understand its interactions with the local processes and its contribution to the protection of the coast. Some defense works, in fact, are effective as far as maintenance works are guaranteed, and their efficacy is deeply linked to the morphological system in which they are built (e.g. dykes that protect the shorelines).

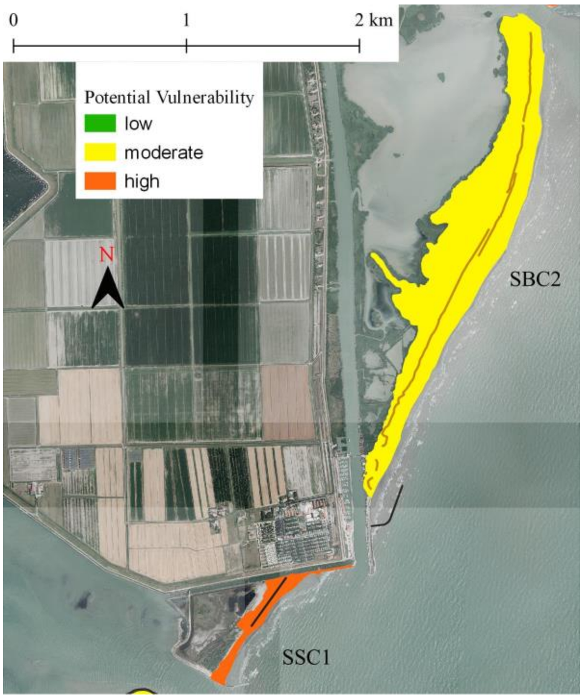


Figure 3-76: Potential vulnerability, before considering the contribution of the defense structures and the dunes. Spiaggia di Barricata and Spiaggia delle Conchiglie

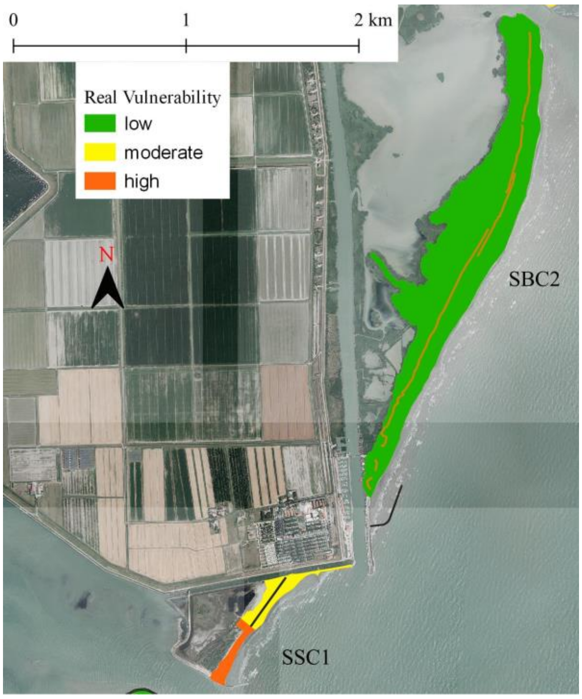


Figure 3-77: Real vulnerability, after taking into account the contribution due to defense structures and dunes. Spiaggia di Barricata and Spiaggia delle Conchiglie

3.5.5 Long-term vulnerability: flooding scenario for the Po Delta

The flooding map published in Marsico et al. (2017) represents the drowning lands for three different sea level scenarios (Figure 3-78). The authors used the worst IPCC projections (AR5 RPC 8.5 scenario) and the Rahmstorf (2007) model to account for the flooding expected in 2100. The IPCC scenario provides minimum and maximum values of the global sea level rise at 0.53 and 0.97 m, while the Rahmstorf (2007) scenario predicts an increase of 1.4 m. To evaluate the relative sea level rise along the Po Delta, the authors combined these three mean absolute values of the sea level rise with the vertical motions expected in the investigated area, thus encompassing the isostatic, tectonic, and eustatic-steric rates. A similar methodology has been used by Da Lio et al (2019), who computed the relative increase of the future sea level taking into account the subsidence rates predicted in the Po River Delta. Finally, the extension of the potentially flooded lands was derived by employing high-resolution Digital Terrain Models (DTM) at a spatial resolution of 1 × 1 m and a vertical accuracy (v.a.) ± 0.1 m.

The map reported here is an extract of the one published by Marsico et al. (2017).

The Po Plain, being already below the mean sea level, is foreseen to be almost completely flooded in the future. The inundated areas predicted for the three different flooding scenarios have similar extension, covering the flat region with its topographic depressions and stretching inland to the Rovigo town. The limit of the flooded land could represent the future coastline in 2100 as speculated by the authors, but also the extension of the potential areas that could be affected by extreme storm surges and high tides before 2100, considering the significant wave heights of episodic events in association to milder sea level scenarios (see in Table 1).

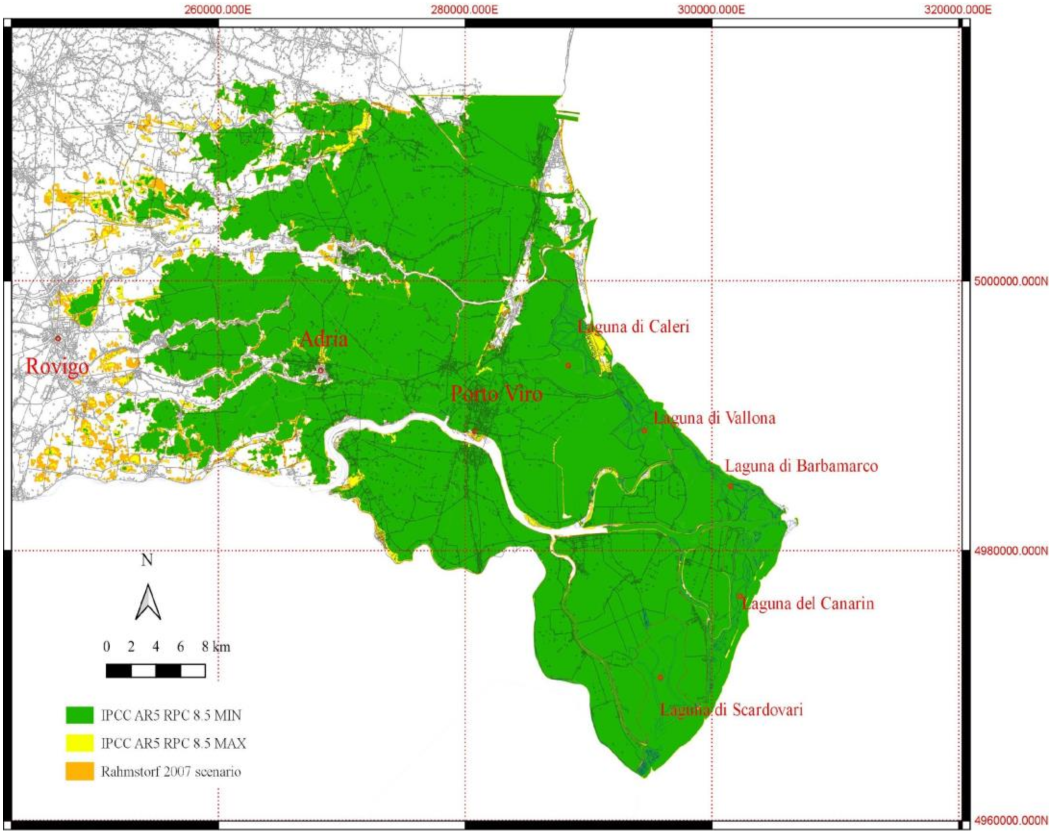


Figure 3-78: Flooding scenario for the Po Delta regions, extracted by the map published by Marsico et al. (2017) with permission of the authors.

Already today large portions of the Po Delta territory are reliant on a complex drainage system made up of several pumping stations, while coastal dykes are fundamental to prevent marine ingression in the transitional areas. Since low-lying areas will increase in the next 50 years, the number and the efficiency of the water pumps operating in the region need to be increased to guarantee the same conditions as today. Moreover, dike elevation should presumably be enhanced to cope with the relative sea level rise.

The used DTM did not consider the almost 60 km of protection dykes (seawalls known as “first defense”) that protect the inland region of the Po Delta, and that have an average height of about 4 m. An analysis of the efficacy of these dykes has been recently begun with the support of numerical simulations to assess the relative sea level raise in the lagoons.

3.5.6 References

- Antonioli, F., Anzidei, M., Amorosi, A., Lo Presti, V., Mastronuzzi, G., Deiana, G., De Falco, G., Fontana, A., Fontolan, G., Lisco, S., Marsico A., Moretti M., Orrù P.E., Sannino G.M., Serpelloni E., Vecchio A., 2017. Sea-level rise and potential drowning of the Italian coastal plains: Flooding risk scenarios for 2100, Quaternary Science Reviews, 158, 29–43, doi:10.1016/j.quascirev.2016.12.021.
- Da Lio, C., Tosi, L., 2019. Vulnerability to relative sea-level rise in the Po river delta (Italy). Estuarine, Coastal and Shelf Science 228, 106379. https://doi.org/10.1016/j.ecss.2019.106379.Fontolan et al. (2014)
- Fontolan G., Bezzi A., Martinucci D., Pillon S., Popesso C. (2014) Individuazione delle unità di gestione della zona costiera del Delta del Po, descrizione fisiografica, trend evolutivo e quantificazione dei budget sedimentari. Rapporto Tecnico per Regione Veneto, UP Genio Civile di Rovigo
- Gallina, V., Torresan, S., Zabeo, A., Rizzi, J., Carniel, S., Sclavo, M., Pizzol, L., Marcomini, A., Critto, A. 2019. Assessment of Climate Change Impacts in the North Adriatic Coastal Area. Part II: Consequences for Coastal Erosion Impacts at the Regional Scale. Water 2019, 11, 1300. https://doi.org/10.3390/w11061300
- Gallina, V., Torresan, S., Zabeo, A., Critto, A., Glade, T., Marcomini, A. 2020. A Multi-Risk Methodology for the Assessment of Climate Change Impacts in Coastal Zones. Sustainability, 12, 3697. https://doi.org/10.3390/su1209369
- Marsico, A., Lisco, S., Lo Presti, V., Antonioli, F., Amorosi, A., Anzidei, M., Deiana, G., De Falco, G., Fontana, A., Fontolan, G., Moretti, M., Orrù, P., Serpelloni, E., Vecchio, A., Mastronuzzi, G., 2017. Flooding scenario for four Italian coastal plains using three relative sea level rise models. Journal of Maps, 13 (2), 961-967. https://doi.org/10.1080/17445647.2017.1415989.
- Piano di gestione del distretto idrografico del Fiume Po, Stato delle risorse idriche, 2016. Autorità di Bcino del fiume Po. Parma, 26 p
- Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea level rise. Science, 315, 368–370. doi: 10.1126/science.1135456 Rizzi et al. (2017)
- Ruol, P., Pinato T., 2016. Gestione integrata della fascia costiera, progetto per lo studio ed il monitoraggio della linea di costa per la definizione degli interventi di difesa dei litorali dall’erosione nella regione Veneto. Padova: 375p.
- Torresan, S., Gallina, V., Gualdi, S., Bellafiore, D., Umgiesser, G., Carniel, S. , Sclavo M, Benetazzo A, Giubilato E, Critto A. Assessment of Climate Change Impacts in the North Adriatic Coastal Area. Part I: A Multi-Model Chain for the Definition of Climate Change Hazard Scenarios. Water. 2019; 11(6):1157. https://doi.org/10.3390/w11061157.

3.6 Po River Delta site Emilia Romagna (RER part)

3.6.1 General site description

The Po Delta Park of the Emilia-Romagna Region is a protected natural area established in 1988 of about 54,000 hectares. The park is included in the municipalities of Cervia, Ravenna and Alfonsine in the Province of Ravenna, and in the municipalities of Argenta, Ostellato, Comacchio, Codigoro, Goro and Mesola in the province of Ferrara. On 2 December 1999 the park of the Po delta became part of the UNESCO World Heritage List. The territory of Po Delta Park extends over a heterogeneous area embracing environments rich in biodiversity, from wetlands to pine forests, from brackish waters to fresh waters. In the northermost part of its territory is located the Sacca di Goro lagoon, the pilot site of Emilia-Romagna. The lagoon has a total area of 26 square kilometers and falls within the administrative borders of the Municipality of Goro and of the Province of Ferrara (Figure 3-79).

The Sacca of Goro is a shallow-water lagoon, with an average depth is approximately 1.5 m. It receives freshwater inputs from the Po di Goro (the Southern Po River branch), which is bordering the lagoon on the north-east and from the Po di Volano, an artificial canal laying in the ancient bed of a former Po River branch. The Po di Volano Canal is hydraulically regulated by the Local Water Authority, the Consorzio di Bonifica della Pianura di Ferrara, and is the quantitatively most important freshwater input to the western and central part of the Sacca di Goro.

The current physical structure of the Sacca di Goro is the result of both natural processes and anthropic interventions. The morphological, hydrological and ecological complexity of the lagoon is associated with the intrinsic natural variability, typical of shallow lagoons with limited interchange with the open sea, which naturally promotes the extreme variation of water circulation.

General climatic features, characterize the lagoon as cold-temperate, with temperature annual minimum in January and a maximum in July. The average precipitation is less than 600 mm per year. Near the coast rainfall shows a tendency to concentrate in the winter, with little precipitation in spring. In the last 25 years, an increase of short-term intense meteoric events has been registered, together with an increase of summer peak temperatures.

Figure3-79: Po Delta Park of the Veneto Region (green) and Po Delta Park of Emilia Romagna (red). SCI-SAC and SPA are highlighted with a dashed pattern. Location of the two focus sites of Canarin and Goro (Regional webgis). The two pilot sites of Sacca del Canarin in Veneto Region and Sacca di Goro in Emilia-Romagna Region are also shown.

3.6.1.1 Administration, main economic activities, recent development, land use

The Po Delta of Emilia-Romagna Region extends for about 200 square kilometers, considering the territory between Mesola, the Po di Goro mouth and Porto Garibaldi. This sector is mainly characterized by natural environments such as the lagoon, valleys. wetlands and forests; there are also agricultural areas and urban centers, scattered in the northern sector and more widespread and concentrated in the southern coast (Figure 3-80). The main use of soil are agriculture (more than 40% of total surface – class 211,213,222,242), and wet areas and sea waters (more than 45% class 411, 421, 422, 511, 512, 521, 523), whereas artificial surface reaches the 4% of total surface.

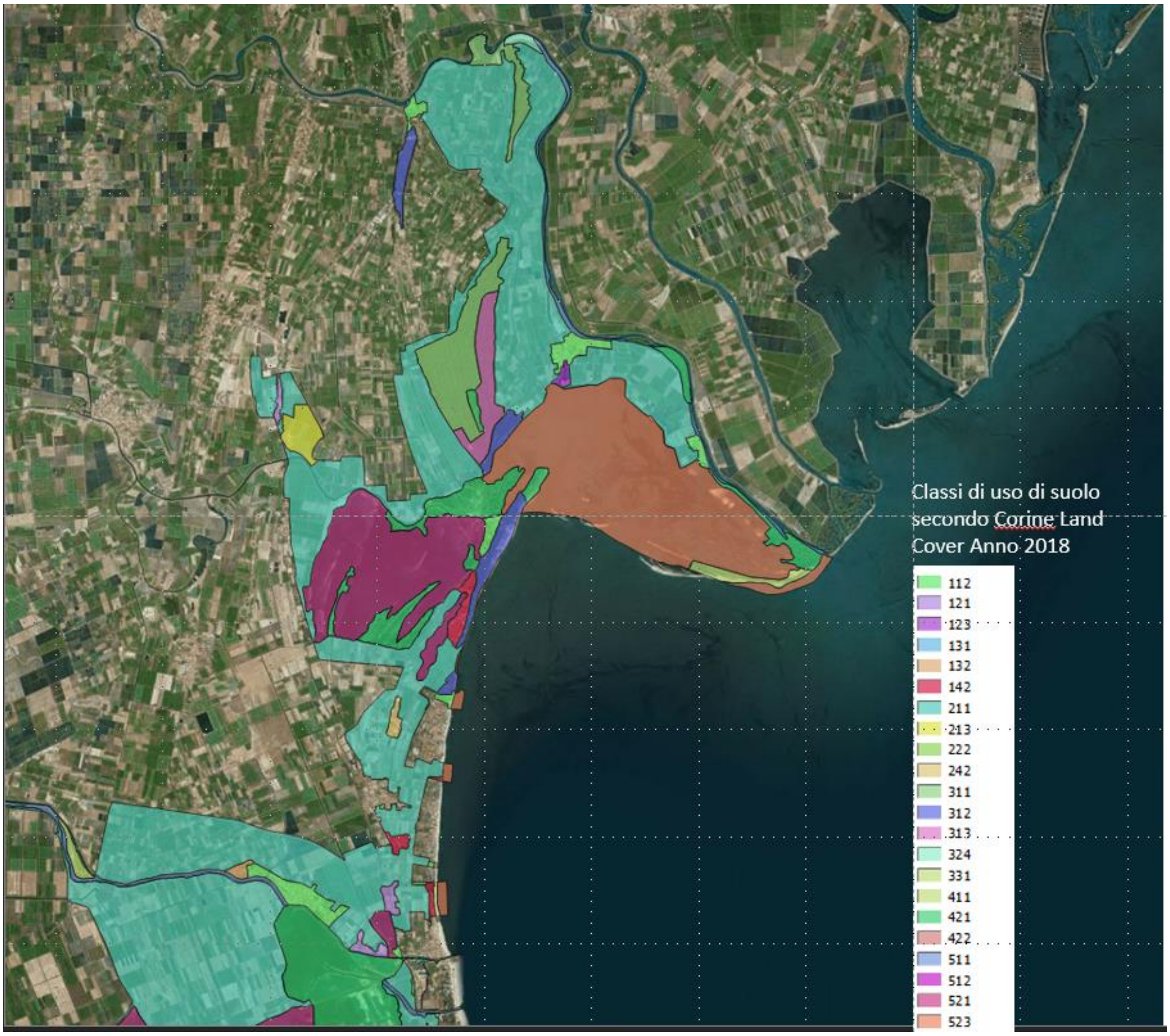


Figure 3-80 Land use cover based on Corine Land Cover Year 2018 in the Po Delta Park of Emilia – Romagna territory.

In the first half of the 20th century, extensive land reclamation works involved the lowlands with the drainage of marsh areas and fish valleys. Today most of the arable lands in Polesine is occupied by monocoltures, consisting in relatively large farms, with a low incidence of tree crops. Maize, wheat and soya prevail throughout the territory, and they are mainly cultivated in large areas alternated with forage crops. Vegetables are widespread close to the coastal areas, thanks to the sandy soil, and they consist in high-quality products, such as asparagus, garlic, pumpkins, watermelons, and melons. Important is the presence of rice fields, fundamental also for the conservation of some bird’s species, although they are under the growing pressure of the salt intrusion. In the past, beet plantations were common, and they were connected to the sugar refineries, which only recently have been dismantled. In the Po River Delta, as in whole the Po plain, the number of small-medium livestock farms has reduced in the last decades, leaving the space to larger farms. Poultry and cattle farms are present, but the latter ones are not connected to the milk production.

Additional activities typically related to fishing, aquaculture, and tourism have occupied a prominent role in the development of the area. A significant production sector includes the fish supply chain, consisting of professional fishing activities and companies operating in the processing and marketing of fish products. The fish sector production, which encompasses traditional and typical products, is quite large and well diversified. In particular aquaculture is well developed in the fishery ponds with precious and common fish species, whereas mussel-farming is widespread in the lagoons (i.e. mullet from Polesine, clams from Goro and other lagoons located in the Veneto part of the delta, blue fish, mussels from Scardovari and Goro, marinated eels, sardines and anchovies from the lagoon of Comacchio (Ferrara) and other managed lagoons for extensive aquaculture in the Veneto portion of thePo delta. The production is based on fishermen cooperatives. The most important fish markets are located in Porto Tolle and Goro. In the Sacca di Goro, by far the most important economic activity is the Manila clam farming, Ruditapes philippinarum, while the traditional fisheries have greatly reduced and currently represent only an integration of the main income, given by clam farming. Manila clam rearing has led to great productive, commercial and social opportunities with the start-up an affirmation of numerous cooperatives of clam farmers and other related activities, such as clams depuration, packaging and trade. Over the past thirty years, the Goro production has established itself at the national level, with shares equal to 50-60% of the entire production, and internationally, as the most important European producer. Currently circa a third of the surface of the Sacca di Goro is licenced for the Manila clam cultivation, to about a thousand farmers, associated in thirty-six cooperatives, with registered office mainly in the municipality of Goro. After the introduction, the Manila clam farming has had an unpredictable development and today all the local economy is based almost entirely on the exploitation of this resource, with an annual production ranging between 10,000 and 15,000 tons.

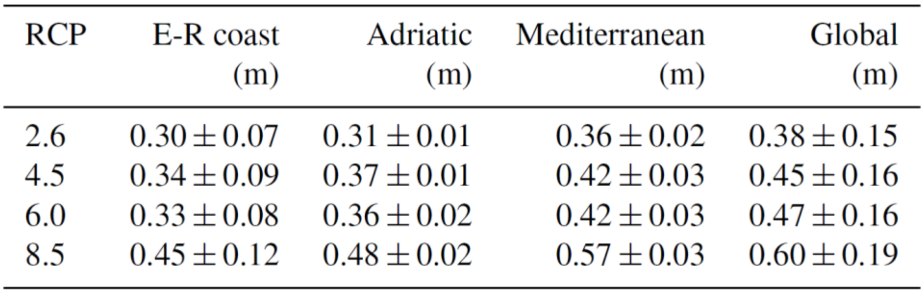
With respect to the ecosystem management of the Sacca of Goro, recently, through the Life Project AGREE, on the basis of monitoring results, a substantial change has been adopted. Two water gates between the Po di Goro and the Valle di Gorino have been opened almost permanently with the aim of increasing the freshwater inflow and favouring restoration of reed stands in the eastern part of the lagoon. At the same time, negotiations have started with clam farmers, to move some of the rearing areas from internal zones of the lagoon to offshore areas, located right in front of the Scannone di Goro. This action was undertaken mainly to avoiding further the risks related to seaweed blooming but, at the same time, it has brought a further decrease of human presence and relative impacts within the lagoon. Tourism in the area is another important economic source, and it is connected mainly to seaside tourism and tourism related to the valorisation of the Po Delta Parks (both of Veneto and Emilia-Romagna regions) from a historical and naturalistic point of view. A secondary sector based on small and very-small enterprises has developed in various fields such as the chemical, metalworking and textile one, and it is mainly founded by local entrepreneurs.

3.6.1.2 Main problems and management objectives

Refer to paragraph 3.5.

3.6.2 Assessment of sea level rise scenarios in the considered coastal and transitional areas

Emilia-Romagna Region also considered the projections and sea-flooding maps proposed by Perini et al. (2017). Sea level rise at 2100 is derived from the IPCC prediction adapted at local scale up to the regional coast (Figure 3-81).



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

Figure 3-81 Sea level predicted during the time interval 2081-2100 with respect to 1985-2005, according to the IPCC RCPs (Perini et al., 2017).

3.6.3 Long-term sediment fluxes and identification of erosional and depositional hot spots

An assessment of the morphological response of the Po River Delta to the future sea level rise was not possible within the activities of this project, considering the morphological complexity of the region, combined with the fragmentation of information on sediment fluxes, and the lack of a morphological model for the whole delta. However, some general observations can be drawn on the basis of past studies and recent observed trends commented in Report 3.2.1 and 3.2.2.

The relative sea level increase would presumably bring to a decline of salt marshes and tidal flats, and to a morphological simplification of the lagoons, deriving from the flattening of their bottom and the siltation of the channels. An anticipation of this trend has been observed before the 70’s, when the Po Delta experienced high subsidence rates, sinking for several decimeters, and going under the water. During that period, a strong degradation of the coastal dunes and barriers was observed, together with the loss of tidal landforms.

The trend that was reduced thanks to a change of policy and several concrete interventions can become worst in the future, especially in case of erosion, submergence or overstepping of the barrier islands due to the sea level rise, which now provide a protective function to the lagoons. Finally, since the morphological response of the transitional system is strongly entangled with the sediment fluxes coming from the rivers, the natural resilience of the lagoons would depend deeply on the sediment availability.

The evaluation of the sediment transport in the Po Delta region is the object of the institutional activities currently carried out by the Authority for the Po River basin (Adpo), which is developing a plan for the sediment management dealing also with the expected future changes.

3.6.4 Short term and long term vulnerability

3.6.4.1 Short-term vulnerability

The Coastal Vulnerability Index (CVI) is one of the simplest and commonly used methods to assess coastal vulnerability to sea level rise driven erosion and/or inundation. In the framework of the Change We Care project, the working group of Veneto Region, supported by the University of Trieste, has computed this index for the Po Delta following the methodology developed by the Friuli Venezia Giulia Region and the University of Trieste and based on the Gornitz approach.

A similar approach was applied for the Emilia-Romagna coast. Total susceptibility was defined as a combination of susceptibility to coastal erosion and sea flooding, in turn calculated on the base of variables of morphology, littoral dynamics and anthropogenic pressure. In addition to this parameter, the 'pessimistic' case was developed, the 'Real Unprotected Susceptibility', which basically simulates that all defense interventions fail or are totally inefficient. For more details, refer to the downloadable document at the link: La costa — Ambiente (regione.emilia-romagna.it).

In the study area, this classification, however, concerns only the Volano spit and the southern coast and excludes a large part of the lagoon and the Goro spit. For these sectors, the state of criticality and short-term vulnerability are described by the regional technical cartography (https://geo.regione.emilia-romagna.it/cartografia_sgss/user/viewer.jsp?service=costa Figure 3-82). These maps summarize most of the erosional and instability processes on the coast, the sea-flood scenarios, the shoreline and sea-bottom trends as well as the hydrological and morphological impacts due to storms.

In addition to these tools, the Emilia-Romagna Region has developed the Sicell classification for coastal management purposes. With this approach, the coast is divided considering physical characteristics, morphological elements, type of defences, engineering interventions, sedimentary balance and management aspects. The cartography and the forms relating to the cells provide important information about the state and the tendency of each cells as growth, stability, precarious balance and erosion (Figure 3 83).

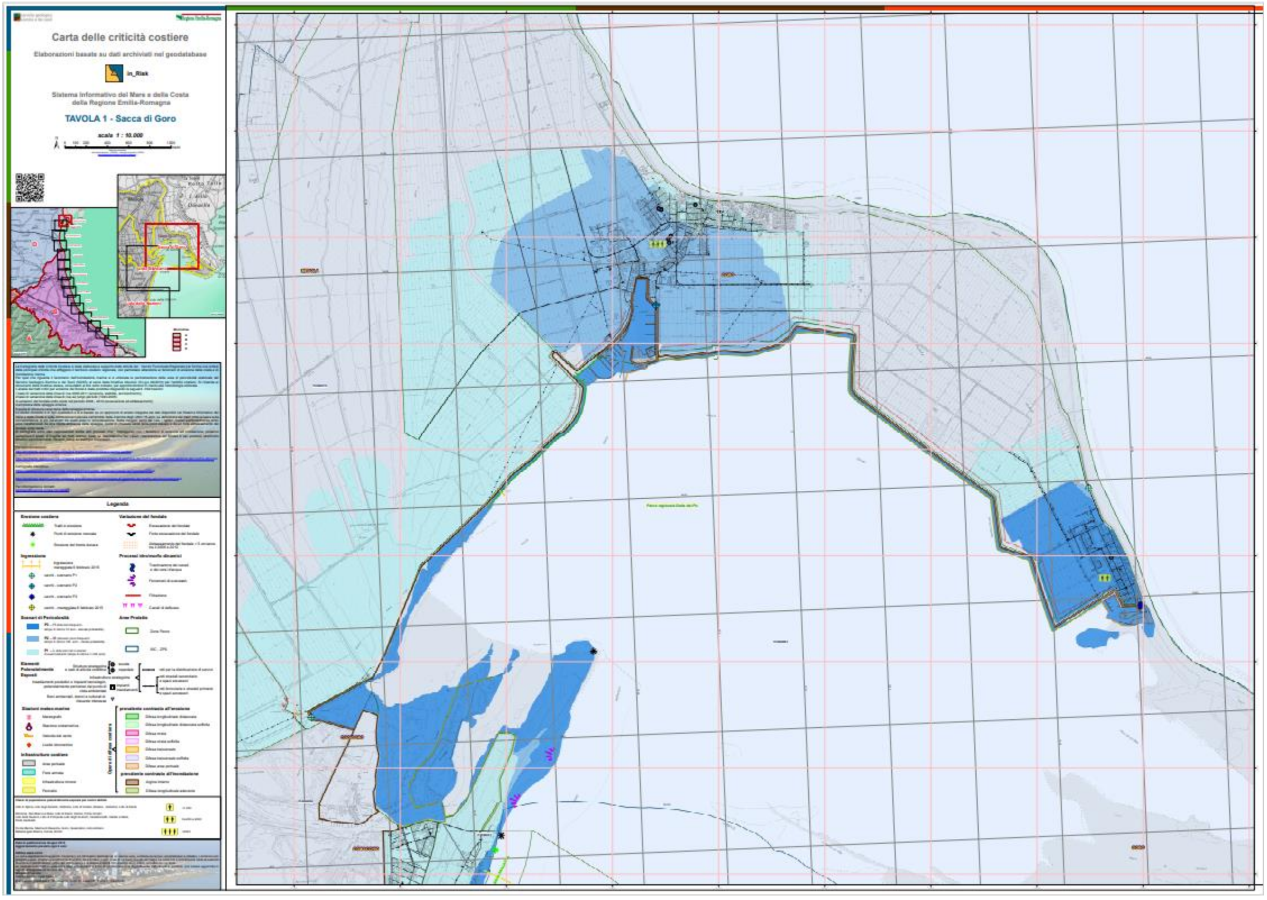
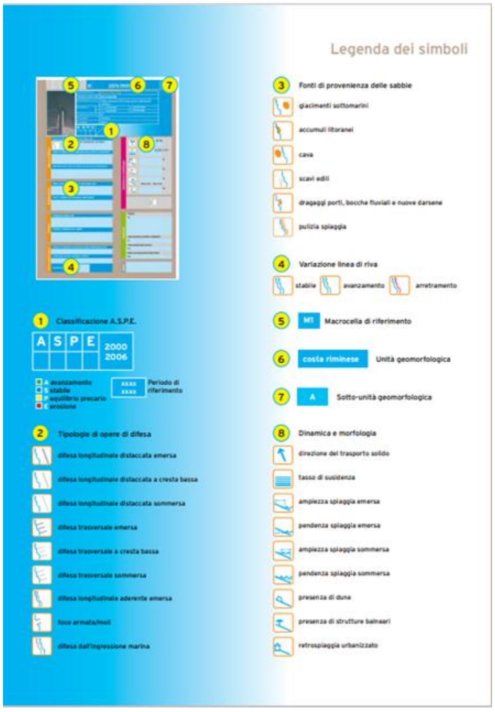


Figure 3-82 Coastal Criticality Map of Emilia-Romagna Region, "Tavola 1 Sacca di Goro".



Legenda dei simboli

① Classificazione A.S.P.E.

A	S	P	E	2000 2006

- 🟩 A avanzamento
- 🟦 S stabile
- 🟨 P equilibrio precario
- 🟥 E erosione

xxxx xxxx Periodo di riferimento

② Tipologie di opere di difesa
- difesa longitudinale distaccata emersa
- difesa longitudinale distaccata a cresta bassa
- difesa longitudinale distaccata sommersa
- difesa trasversale emersa
- difesa trasversale a cresta bassa
- difesa trasversale sommersa
- difesa longitudinale aderente emersa
- foce armata/moli
- difesa dall'ingressione marina

③ Fonti di provenienza delle sabbie
- giacimenti sottomarini
- accumuli litoranei
- cava
- scavi edili
- dragaggi porti, bocche fluviali e nuove darsene
- pulizia spiaggia

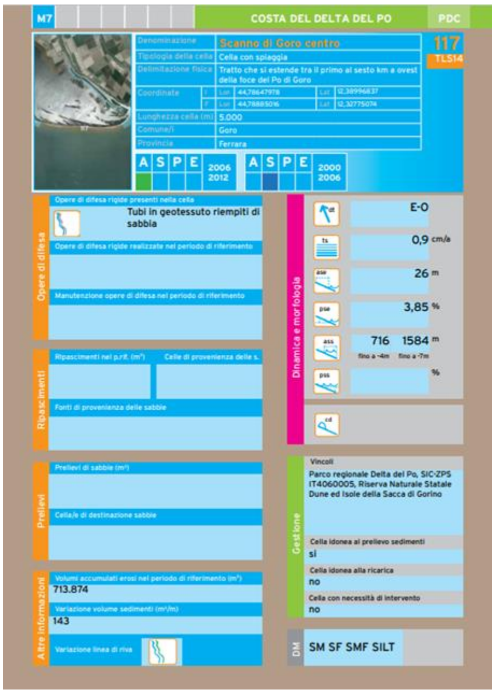
④ Variazione linea di riva
- stabile
- avanzamento
- arretramento

⑤ M1 Macrocella di riferimento

⑥ costa riminese Unità geomorfologica

⑦ A Sotto-unità geomorfologica

⑧ Dinamica e morfologia
- direzione del trasporto solido
- tasso di susidenza
- ampiezza spiaggia emersa
- pendenza spiaggia emersa
- ampiezza spiaggia sommersa
- pendenza spiaggia sommersa
- presenza di dune
- presenza di strutture balneari
- retrospiaggia urbanizzato



M7 COSTA DEL DELTA DEL PO PDC

117
TLS14

Denominazione	Scanno di Goro centro			
Tipologia della cella	Cella con spiaggia			
Delimitazione fisica	Tratto che si estende tra il primo al sesto km a ovest della foce del Po di Goro			
Coordinate	I	Lon 44,78647978	Lat	12,38996837
	F	Lon 44,78885016	Lat	12,32775074
Lunghezza cella (m)	5.000			
Comune/i	Goro			
Provincia	Ferrara			

A	S	P	E	2006 2012
🟩				

A	S	P	E	2000 2006
	🟦			

Opere di difesa

Opere di difesa rigide presenti nella cella
Tubi in geotessuto riempiti di sabbia

Opere di difesa rigide realizzate nel periodo di riferimento

Manutenzione opere di difesa nel periodo di riferimento

Ripascimenti

Ripascimenti nel p.rif. (m³) | Celle di provenienza delle s.

Fonti di provenienza delle sabbie

Prelievi

Prelievi di sabbie (m³)

Cella/e di destinazione sabbie

Altre informazioni

Volumi accumulati erosi nel periodo di riferimento (m³)
713.874

Variazione volume sedimenti (m³/m)
143

Variazione linea di riva

Dinamica e morfologia

dt	E-O	
ts	0,9	cm/a
ase	26	m
pse	3,85	%
ass	716 fino a -4m 1584 fino a -7m	m
pss		%
cd		

Gestione

Vincoli
Parco regionale Delta del Po, SIC-ZPS IT4060005, Riserva Naturale Statale Dune ed Isole della Sacca di Gorino

Cella idonea al prelievo sedimenti
si

Cella idonea alla ricarica
no

Cella con necessità di intervento
no

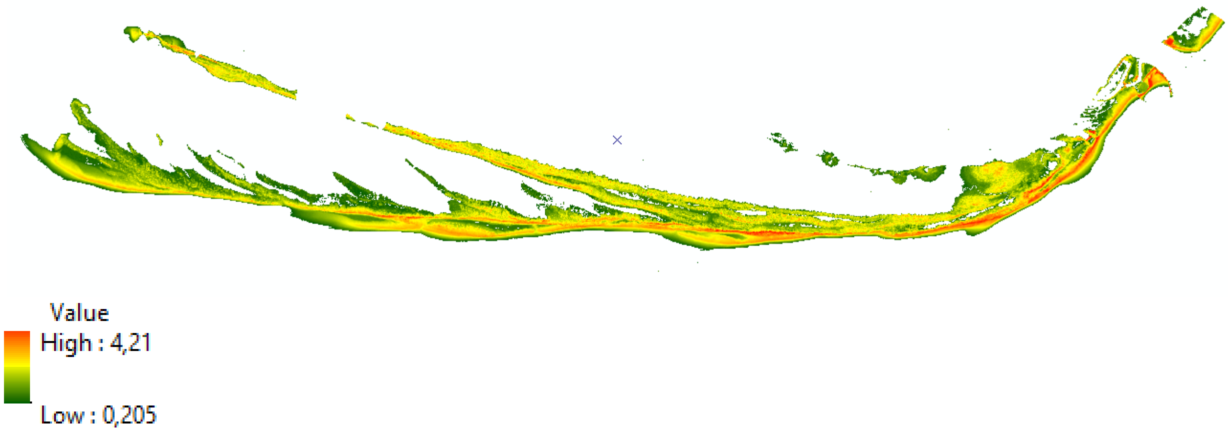
DM SM SF SMF SILT

Figure 3-83 example of Sicell classification within Scanno Spit.

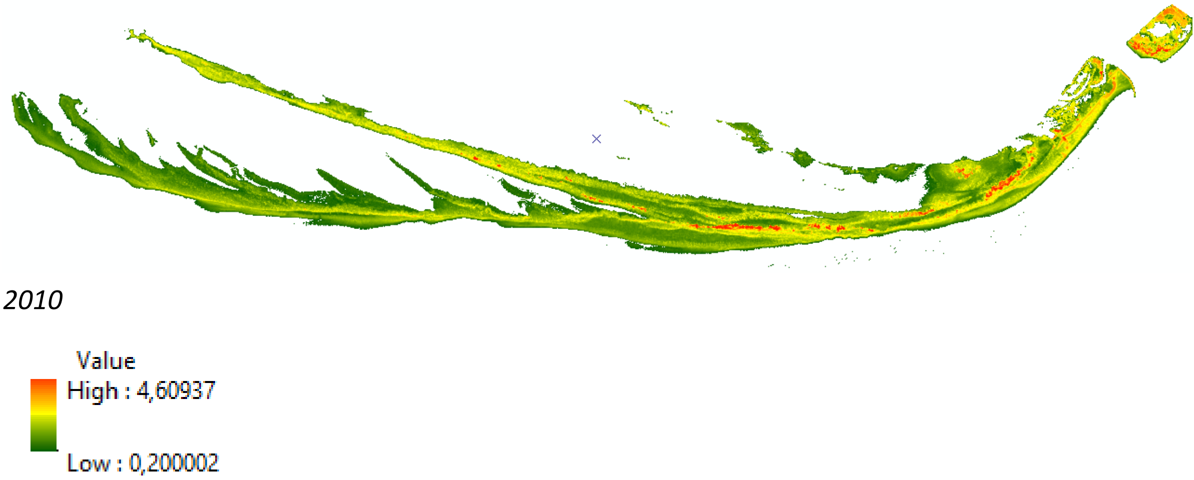
3.6.4.2 Potential vulnerability assessment

A specific study for the Emilia-Romagna coast within this project does not exist. Some considerations may derive from the previous studies and analyzes presented in reports 3.2.1 and 3.2.2. The evolution of the lagoon shore is blocked by the presence of the almost continuous embankment while the Po di Goro mouth and above all the spit show a lively littoral dynamic in the last century. The last few decades have been characterized by a strong remodeling of the spit due to the occurrence of sea storms and to long-shore transit of sand; recently, erosional hot spots have developed at the mouth and in the adjacent part of the spit. This coastal dynamic, together with the morphological characteristics, produces a high vulnerability to erosion and submersion.

The available DTMs (Figure 3-84) show that in six years the sandbar has lost 10 cm on the average altitude: in 2004 the average altitude is 0.92 m, in 2010 the average altitude is 0.82 m. An evolution in this direction would further increase the level of vulnerability in this sector.



Dtm 2010



DTM 2004

Figure 3-84 Altimetry from DTM of 2010 (above) and 2004 (below)

In the spit sea-bottom, the average depth, between 2012 and 2018, does not vary significantly; however, there is a deepening in the upper shoreface between 0 and -3 m and shallowing in the lower shoreface, between -4 and -6 meters. The upper shoreface is the main sector where the sand transport takes place and this trend could mean a decrease in inputs from the north.

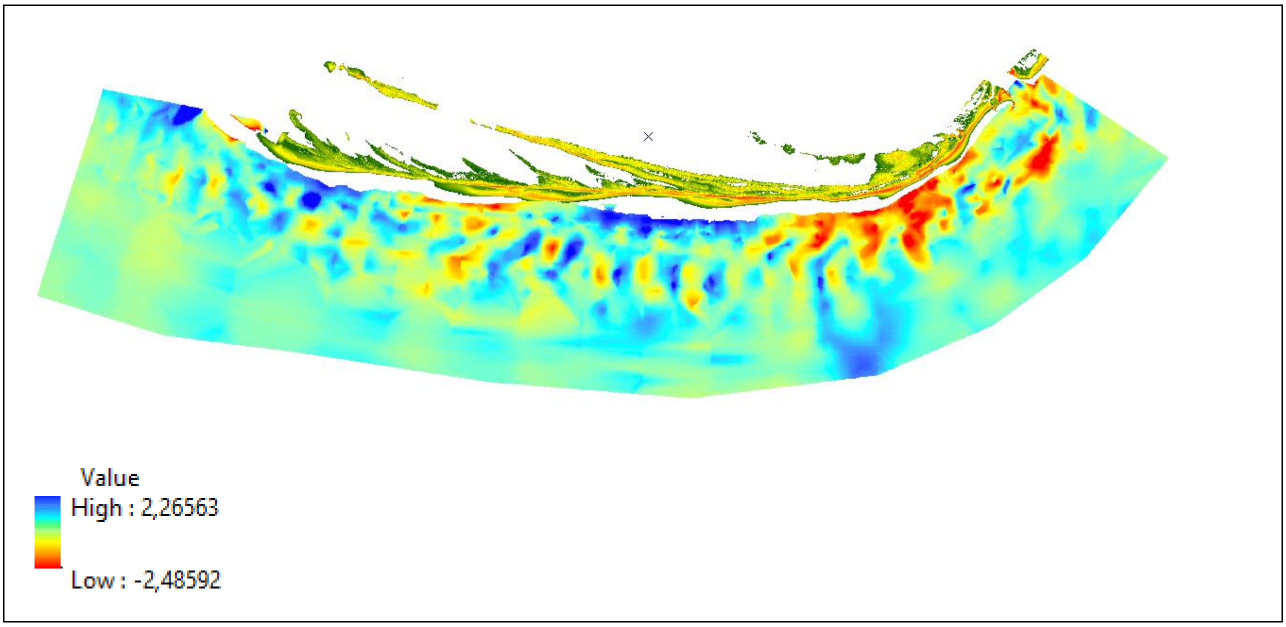


Figure 3-85 Sea-bottom changes in the Goro spit ("Scannone") in the 2012-2018 period (red: deepening, blue: shallowing).

The future of the spit seems to be linked to the supply from the north-east by the long-shore current rather than by the contributions of the Po di Goro delta branch. This working hypothesis is under consideration for future studies. The long-shore transport is also the main control factor of the Volano spit which, being in sedimentary equilibrium and locally in progressive growth in the last decades, testifies to a continuous supply of sand from the south that could be guaranteed also in the coming years. The entire study sector, due to the altitude and subsidence, is liable to marine submersion in the medium and long term. The lagoon embankment protects a large sector from submersion while the natural areas in the littoral spits, which are not protected, are currently exposed to this phenomenon.

3.6.4.3 Real vulnerability

The southernmost coastal sector, belonging to the Emilia-Romagna region, is characterized by embankments to defend the lagoon shores. The marine submersion scenarios developed for the Flood Directive are heavily influenced by the presence of this defense; the damage or ineffectiveness of this work would drastically change the scenarios: the protected areas are located below sea level and in the absence of embankments or with the presence of gaps, much of the territory of Goro would go under water.

3.6.4.4 Long-term vulnerability: flooding scenario for the Po Delta

Regarding the southern margin of the Po delta, in the Emilia-Romagna Region, the maps produced by Perini et al. (2017) are considered. The map in figure 3.86 includes the study area and shows the increase in floodable areas at 2100 considering a storm with a return time of 100 years, as calculated with the data available today, to which the effects of subsidence and sea level rise are superimposed.

It is evident that much of the coastal area is already submerged with the terrain updated to 2012 and due to a T100 sea-storm scenario (in blue) without considering the impact of subsidence and sea level rise. The projection to 2100 shows a significant increase in the flooded area due to the land lowering alone (green areas) and a further increase by adding the sea level rise, in particular at the mouth of the Po di Volano and on the southern coast (yellow areas - optimistic hypothesis - and red areas - pessimistic hypothesis).

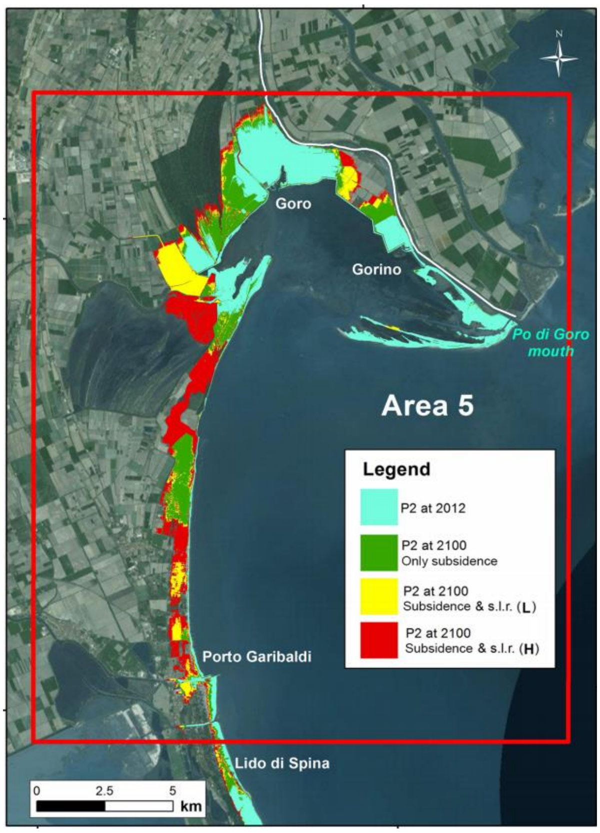


Figure 3-86 The maps produced by Perini et al. (2017)

3.6.5 References

Perini, L., Calabrese, L., Luciani, P., Olivieri, M., Galassi, G., & Spada, G. 2017. Sea-level rise along the Emilia-Romagna coast (Northern Italy) in 2100: scenarios and impacts. *Natural Hazards and Earth System Sciences*, *17*(12), 2271-2287.

4 Conclusion

The coastal zone is the most vulnerable to the climate change, due the exposure to sea level rise (SLR). The vulnerability to the sea level rise is expected to increase progressively for the low lying coastal sectors, especially sandy barrier islands and deltas.

The deltas and the barrier islands are among the coastal areas with the fastest morphodynamics, owing to the significant interplay between the river and the marine processes, and they are also historically of exceptional socioeconomic importance. The deltas are significantly affected by both the climate change at different time scales and the human activities ranging from millennia to a few years.

The long-term (multi-decadal or longer time scales) changes in the river influence due to the climate and the land-use modifications may induce the rapid morphological changes and cause the alternate phases of erosion and deposition

For some of the pilot sites the most relevant issue is represented by a general lack of data availability and continuity (Neretva, Mula Muggia). Both are required to determine the baseline condition for sediment flux, hydrology and meteorology. The delta systems are very sensitive to the relative sea level rise (RSLR), i.e. the combination of sea level and the vertical ground movement changes. Specifically, the delta areas are naturally prone to sink because of the high long-term secondary consolidation of the recent Holocene deposits.

With regard to climate change, from 1985 to 2020 the AdriSC simulation indicates rising values of the mean annual temperature, strong interannual variability of the surface salinity, a constantly sea level rise with strong interannual variability. As for the intensity of storm surges and flooding of the coastal area, they will not significantly change the intensity in the future climate. But combined with the rising sea levels, the flooding of the coastal area will increase many times over.

Different vulnerability aspects are predicted to increase in the pilot sites. The human development is a factor that contributes to this. The historical socio-economical changes have often become the dominant forcing factors for the coastline evolution and the loss of wetland habitat.

The sea level rise is the most important vulnerability issue for coastal area. An assessment of relative sea level rise scenarios in 2100 is proposed for the Adriatic sandy beaches of the Po Delta and the Mula di Muggia pilot sites, with an evaluation of the two components: sea level rise and short-term and long-term land subsidence. Besides sea level rise, wave climate and its variations can play an important role in controlling coastal dynamics and possibly affecting the stability of the coasts and the safety of the infrastructures. At the present state of the art, a local assessment of the future wind wave regimes in the nearshore is not available. Nevertheless, some important indications can be obtained from the WP 4.1, which includes an analysis of the effects of climate change on hydrodynamic processes at the Adriatic basin scale and offshore of each pilot site.

The ability of coastal sedimentary systems to adapt with sea-level rise is directly tied to sedimentary longshore availability, which is primarily provided by fluvial supplies. Hence, the existence of deltas depends on the equilibrium between the loss in elevation of the delta terrain with respect to the mean sea level and the sedimentary supply. At the same time, if the sediment supply and the degree of freedom are properly ensured, the barrier islands can adapt, modifying in shape, position and elevation.

The building of hydropower plants on rivers and their tributaries has had a significant impact on discharge, resulting in a reduction in water and sediment supply to the coastal zone (Neretva, Po, Isonzo). This reduction is limiting delta progradation or causes erosional phases (Neretva). Morphological signals of a re-equilibrium and new progradation behaviours of deltas and their associated landforms are observed on the Po and Isonzo deltas, but cannot be confirmed by sufficiently data on sediment discharge. Higher sediment fluxes are expected during rainy seasons, and especially during storms characterized by extreme rainfall, but it cannot be confirmed from data (Jadro).

For all of these reasons, quantifying the sediment supply from rivers is one of the most essential challenges due to a general absence of measured data (Neretva, Jadro, Isonzo, Po), as well as studies on substrate erosion in the topographic catchment. To, partially, fill this gap, some initiatives were implemented in the project as the ADCP installation at the mouth of the Isonzo river (Mula di Muggia).

In general, the **water balance**, which is determined by the equilibrium between rain and evapo-traspiration, is expected to worsen as temperatures rise. In the dry summer period, critical situations occur, particularly in July and August, when the natural discharges of the springs are low, water and air temperatures are high and water demands increase (Neretva, Jadro). Intensive agriculture and tourism are the two most recognised human causes of water consumption, which is expected to worsen in the future. At the same time, decrease of river water discharge favours the penetration of the sea water wedge, upstream along the river (Neretva).

Sea level rise affects the base level and consequently determine new water balance in coastal water bodies, as in the case of the Vransko lake. Hydrologic balance assessment is difficult, particularly in the karstic area (Vransko), where problems caused by climate change / sea level variation are complicated by the karst aquifer's complex structure and interrelationships with the lake system, the sea, and the inflow from the basin, which are only partially hydrologically observable and known. In particular, with the increase of temperature and sea level, the equilibrium between the lake and the sea would be established at slightly higher water levels in the lake and the penetration of saline sea water into the lake system would be increased.

Past and recent urban development in coastal areas are increasing the vulnerability of **infrastructure and buildings** with regard to the increased intensity of torrential waters on land and the expected sea level rise (Jadro, Mula Muggia). In addition to the built-up parts of the coast, the beaches will be repeatedly endangered by the erosion of the coast in the case of the projected sea level rise (Jadro, Mula Muggia).

The effects on **tourism** will be twofold. Due to the increase in air and sea temperature, it will be possible to extend the tourist season both in the preseason and in the postseason. The negative effects will be concentrated in the summer, when the heat waves will be many times more intense and long-lasting than in today's climate.

Agriculture will be endangered (Jadro) due to the increase in air temperature and heat waves, and the reduction of precipitation in the warm part of the year, and thus increased evapotranspiration (evaporation).

Finally, projected climate change will cause changes in the **composition and abundance of plant and animal species**, where organisms that are more resistant to high temperatures and prolonged drought periods will prevail. In the sea, rising temperatures and salinity will affect biodiversity, especially in the coastal area. It will occur an expansion of thermophilic species towards coastal areas (Jadro).

A tool to address and adapt to the climate change is an adequate coastal zoning as a basis for mitigation intervention and future planning.

The first step provided a **short-term vulnerability assessment** by applying the Coastal Vulnerability Index to coastal homogeneous tracts, which is based on data concerning the upper-shoreface sediment budget as well as the morpho-evolutive properties of beaches and barrier islands (Delta Po, Mula Muggia).

The coastal zone altimetry is the primary tool for assessing long-term vulnerability in low-lying areas (Po Delta, Mula di Muggia). It was derived from the most recent Digital Terrain Model and enables the generation of flooding maps in relation to long-term (2100) relative sea level rise. The maps are derived from scientific literature (Delta Po) or developed specifically for the project pilot sites (Mula Muggia).

For the **long-term vulnerability assessment,** the coastal zone altimetry represents the fundamental tool for the low lying territory (Po Delta, Mula di Muggia). It was obtained from the most recent Digital Terrain Model and allows the production of flooding maps with respect to long-term (2100) relative sea level rise. These are presented from scientific literature (Delta Po) or elaborated for the area (Mula Muggia).